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A NOVEL METHODOLOGY FOR THE ASSESSMENT OF THE DIRECT AND INDIRECT IMPACTS ASSOCIATED WITH THE DEPLETION OF FOSSIL RESOURCES IN LIFE CYCLE ASSESSMENT

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A NOVEL METHODOLOGY FOR THE ASSESSMENT OF THE DIRECT AND INDIRECT IMPACTS ASSOCIATED WITH THE DEPLETION OF FOSSIL RESOURCES IN LIFE CYCLE ASSESSMENT

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DEDICATION

I dedicate this thesis to the two pillars of my life that have supported me throughout the process:

my family, for their love and support, and especially:

my father - for inspiring me to pursue education and for motivating scientific curiosity;

my mother-for teaching me to be content and peaceful even through the toughest times;

my brother- for being a great advisor to me in my career,

and my friends- for their love, and for their role in making some of the greatest memories of my lifetime to date; but also for the their presence and support through the difficult times

.

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RÉSUMÉ

Ce projet de maitrise présente une méthode innovante servant à évaluer les impacts environnementaux du cycle de vie associés à l'épuisement des ressources fossiles. Cette méthode est basée sur une perspective fonctionnelle visant à améliorer l'état de l'art actuel.

L'épuisement des ressources fossiles en ACV représente une part significative des impacts dans la catégorie utilisation des ressources et les méthodes d'impacts actuelles en ACV ne prennent pas en compte l'épuisement des ressources fossiles de façon satisfaisante.

Dans cette recherche, l'ensemble des méthodes d'impacts dans l'analyse du cycle de vie (ACVI) existantes, sont analysées et les problèmes fondamentaux à résoudre seront identifiés.

Un nouveau cadre méthodologique en ACV est alors proposé pour les impacts directs et indirects qui sont associés à l'épuisement des ressources fossiles. Pour les impacts directs, de la catégorie problème, les facteurs de caractérisations proposés représente la quantité de ressources fossiles (en MJ) qui va priver les générations futures de la ressource qui a été dissipée.

Au niveau dommage, les facteurs de caractérisation proposés représentent les couts additionnels totaux (en dollars US), que la population mondiale future serait prête à payer seraient prête à payer suite à la raréfaction de la ressource fossile par MJ de ressources disparues. Les impacts indirects liés à l'épuisement de la ressource fossile sont définis comme étant les impacts du cycle de vie de l'adaptation du marché de l'énergie en raison de l'augmentation marginale du prix de la ressource fossile. Les facteurs de caractérisation obtenus sont ensuite comparés aux précédents facteurs donnés par les précédentes méthodes d'impacts en ACV. Un exemple illustratif est présenté afin de démontrer comment les facteurs de caractérisations sont utilisés dans le but de calculer les impacts effectifs aux utilisateurs d'une certaine quantité de ressource fossile dans un pays donné.

Les résultats de cette étude, contribuent à l'amélioration des connaissances actuelles des impacts d'ACV face à l'épuisement de la ressource fossile. En développant une régionalisation ainsi qu'une différenciation entre les ressources fossiles, cette étude intègre une substituabilité des ressources basée sur une approche fonctionnelle et la comptabilité de l'élasticité entre le prix et la consommation de la ressource. Cette méthodologie sera utilisée dans le développement d'impacts concernant l'épuisement des ressources fossiles au sein de la nouvelle méthode d'évaluation des impacts IMPACT World+.

À la fois aux niveaux problème et dommage, les résultats montrent que la discrimination régionale a un impact significatif sur les résultats, ce qui améliore les méthodes existantes en y ajoutant une précision régionale.

Au niveau dommage, les couts additionnels dus à la raréfaction des ressources, se trouvent être différents selon les diverses ressources fossiles ce qui améliore les méthodes existantes utilisant le même facteur de caractérisation pour toutes les ressources fossiles. La prise en compte l'effet de substitution parmi les ressources fossiles et parmi les sources d'énergies alternatives (nucléaires, renouvelables) en fonction de leur application, ainsi que la considération de l'effet d'élasticité entre l'offre et la demande ont une influence significative sur les résultats au niveau dommage.

ABSTRACT

This master's project presents a novel method for assessing the environmental life cycle impacts associated with the depletion of fossil resources based on a functional perspective, aiming to enhance the current state-of-the-art life cycle impact assessment (LCIA) methodology. Fossil resource depletion in life cycle assessment (LCA) accounts for a significant portion of the impacts in the impact category of resource use and current LCIA methods do not address fossil resource depletion satisfactorily.

For this research, existing LCIA methods were analyzed and the key issues to be addressed were identified. A new LCIA framework is subsequently proposed for the direct and indirect impacts associated with the depletion of fossil resources. For direct impacts, at midpoint, the proposed characterization factors represent the amount of fossil resources (in Mega Joules) that is deprived from future users per MJ of a resource that is dissipated. At endpoint, the proposed characterization factors represent the total additional costs (in US Dollars) that the world has to pay as a consequence of the deprivation of a fossil resource from future users per MJ of the resource that is dissipated. The indirect impacts associated with the depletion of fossil resources are defined as the life cycle impacts of the adaptation of the energy market as a consequence of the marginal increase in the price of a fossil resource. The obtained characterization factors are compared with those from previous LCIA methods. An illustrative example is presented to demonstrate how the characterization factors are used to calculate the impacts for the users of a certain fossil resource in a certain country.

At midpoint, and endpoint, results demonstrated that regional discrimination had a significant impact on results, improving existing methods by adding regional accuracy. At endpoint, the additional costs due to depletion were found to be different for different fossil resources, improving existing methods that use the same characterization factor for all fossil resources. Taking into account the effect of substitution among fossil resources and among alternative energy sources (nuclear, renewables) according to their application, and taking into account the effect of elasticity between price and demand had a significant influence on endpoint results.

The outcome of this research contributes to the enhancement of state-of-the-art LCIA for fossil resources depletion by differentiating regionally, differentiating between fossil resources, incorporating resource substitutability based on a functional perspective, and accounting for elasticity between the price and consumption of a resource. This methodology will be used in developing the LCIA methodology for fossil resources depletion in IMPACT World+ impact assessment method.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

ALCA – Attributional Life Cycle Assessment

CF – Characterization Factor

CLCA – Consequential Life Cycle Assessment

DALY – Disability Adjusted Life Year

FOCSI – Fossil Resource Competition Scarcity Index

HHV – Higher Heating Value

ILCD- International Reference Life cycle Data System

LCA – Life cycle assessment, sometimes referred to mistakenly as Life Cycle Analysis

LCIA – Life Cycle Impact Assessment

LHV – Lower Heating Value

LL – Lower Limit

MFA – Material Flow Accounting and Analysis

MPI – Marginal Price Increase

R/P – Reserves over production ratio

TAC – Total Added Costs

TACON –Total Additional Consumption

UL – Upper Limit

WEPS – World Energy Systems Plus – the energy forecast model used to conduct analysis

APPENDICES

CHAPTER 1 INTRODUCTION

This thesis presents a new methodology for the assessment of the life cycle impacts due to fossil resources depletion in life cycle assessment.

Fossil resources are non-renewable resources with limited global reserves. Economic reserves to production ratios, used as a rough estimate for assessing the scarcity of fossil resources, are calculated as 46.2 years for petroleum, 58.6 years for natural gas, and 118 years for coal (BP, 2012)**.** Moreover, it is predicted that between 2008 and 2030, the global consumption of petroleum, coal and natural gas will continue to grow. There are impacts, and life cycle assessment is a strong tool for assessing the impacts associated with a resource becoming less available for future users.

Life Cycle Assessment (LCA) is a tool for assessing the environmental impacts associated with products and services throughout their life cycle. A recent review presented on current life cycle impact assessment (LCIA) methods by the International Reference Life Cycle Data system (ILCD) handbook has concluded that none of the current LCIA methods assess the impacts of fossil resource depletion in a satisfactory manner (ILCD, 2010, 2011). Yet in most LCA studies, the impacts due to the depletion of fossil resources are the dominating impacts in the “Resources” damage category. The objective of this research therefore was to enhance the current state-of-the-art methodologies for assessing fossil resource depletion in life cycle assessment (LCA). Following a critique of existing LCIA methods, the key issues to address were identified as: incorporating regional discrimination, incorporating fossil resource discrimination, incorporating substitutability with a functional perspective (Stewart and Weidema, 2005), and accounting for elasticity between the price and consumption of a resource. Another key issue is the consistency of the model used for fossil resources with the models used to assess the depletion of other resources such as water and mineral resources - in the current project, the consistency with IMPACT World+ models for water and mineral resources (IMPACT World +, 2013).

This thesis is divided into 4 chapters. Chapter 1 serves as the introduction chapter of the thesis by presenting a literature review and identifying key research needs. In the methodology chapter (Chapter 2), the tasks performed to reach the research objectives are detailed. In the results and discussion chapter (Chapter 3), the deliverables of the research are presented and evaluated. In the conclusions chapter (Chapter 4), the key findings of the research are presented and recommendations are made for future research.

Chapter 1 begins with a literature review of the key elements that need to be understood in order to appreciate the contents of this thesis. The literature review is followed by a section presenting the key research needs identified prior to conducting this research. In the conclusion of this chapter, the research hypothesis and the research objectives are presented.

LITERATURE REVIEW

This literature review presents the background necessary to understand the contents of this thesis. In section 1.1, a review of fossil resources and their classifications is presented. In section 1.2, the current available reserve estimates of fossil resources and current annual production rates are presented. These concepts will be used in the methodology section for defining the midpoint characterization factor.

In section 1.3 we explore the concepts related to fossil resources depletion and the different viewpoints on fossil resource depletion. Three tools used for predicting the future availability of fossil resources are presented: Reserves-to-production models, curve-fitting models, and energy simulation models. These three distinct tools are used throughout our LCIA methodology.

In section 1.4, life cycle assessment (LCA) is presented as a tool for assessing the impacts associated with the depletion of fossil resources. In section 1.5, life cycle impact assessment (LCIA) is explored further in detail, as the scope of the presented research is focused on this step of LCA. Section 1.6 presents the significance of fossil resource depletion in LCA, leading to the research questions presented in the subsequent section.

1.1 Fossil resources

Resources are defined as elements that are extractable for human use and that have a functional value for society (Udo de Haes, 2006). Resources can be classified according to different qualities:

Biotic and Abiotic: Abiotic resources, which are the product of past biological processes or physical/chemical processes, including resources such as iron ore, crude oil, water, coal, land, and wood; and biotic resources which are living resources, such as trees, plants, and wildlife (Muller-Wenk, 1998; SETAC, 2003).

Funds, flows and stocks: Stocks are defined as resources that are limited, therefore their extraction leads to the reduction of their availability. Funds may be depleted but also have a renewal rate which is high enough to allow the resource to recover. Flow resources cannot be depleted, however their availability per unit time is limited; and thus their extraction is marked by competition (e.g. wind energy) (SETAC, 2003).

Fossil resources, the subject of this study, are *abiotic resources* that are classified as *stocks*. There are three different types of fossil fuels: Petroleum, Coal, and natural gas. The following subsections provide definitions for each fossil resource, examine the products derived from a fossil resource, and explain the worldwide availability of each fossil resource.

1.1.1 Petroleum

Petroleum refers to deposits of oily material found in the upper strata of the earth's crust (Tester, Drake, Driscoll, Golay, & Peters, 2005). Petroleum has a heterogeneous chemical structure, composed of different hydrocarbon chains. Crude petroleum is taken to oil refineries and the hydrocarbon chemicals are separated by distillation and treated by other chemical processes, to be used for a variety of purposes. Table 1 highlights the most important yields from a typical oil refinery in the United States. The largest share of oil products are energy carriers. In fact, 92% of the global production of petroleum is used for energy use and therefore dissipated (IEA, 2009). Energy-carrying fuels include gasoline, jet fuel, diesel fuel, heating oil, and heavier fuel oils. Refineries also produce other chemicals, some of which are used in chemical processes to produce plastics and other useful materials (Tester et al., 2005).

Table 1 - Refinery yields for a typical petroleum refinery in the United States (USEIA, 2012).

Product	Gasoline	Diesel and other fuels	Jet fuel	Heavy fuel oil	Asphalt	Lubricant	Other products

Refinery yield	46%	26%	9%	4%	3%	1%	11%

1.1.2 Coal

Coal is a compact stratified mass of metamorphosed plant that has, in part, undergone arrested decay to different extents of completeness (Tester et al., 2005). Table 2 presents a general classification of coal use worldwide. Coal is primarily used as a solid fuel to produce electricity and heat through combustion for industrial and non-industrial applications. Statistics show that worldwide, more than 99 percent of coal is used for energy purposes and therefore dissipated (IEA, 2009).

Table 2 - World coal use (World Coal Institute, 2009)

Function	Electricity generation	Steel manufacturing	Cement Plants	Other industry	Heating	Other uses
Percentage	68%	7%	4%	8%	3%	10%

1.1.3 Natural Gas

Natural gas is found in underground reservoirs of porous rocks, alone or physically mixed with petroleum. It is developed naturally over millions of years from the carbon and hydrogen molecules of ancient organic matter trapped in geological formations. Natural gas consists primarily of methane, but also ethane, propane, butane, pentanes, and heavier hydrocarbons. A general classification of worldwide natural gas uses is presented in Table 3. Natural gas is used domestically as a cooking and heating fuel. In much of the developed world it is supplied to buildings via pipes where it is used for many purposes including natural gas-powered ovens, heating/cooling, and central heating (USEIA, 2011). It is also used for the generation of electricity. Natural gas is used in the manufacture of fabrics, glass, steel, plastics, paint, fertilizers and other products. Natural gas is also used for transportation. Overall, statistics show that globally, more than 94 percent of the natural gas produced is used for energy purposes (IEA, 2009).

Table 3 - World natural gas use (USEIA, 2012)

Function	Electricity generation	Industrial	Commercial	Chemicals	Transport
Percentage	45%	33%	16%	5%	1%

1.1.4 Conventional versus unconventional fossil resources

From a production perspective, a distinction is made between conventional and unconventional resources. This distinction is explained the following sections. It should be noted that this classification is different from the classification of the economic reserves estimates that is used in the methodology.

Petroleum conventional and unconventional resources: The distinction between conventional and unconventional petroleum resources is based on the density and viscosity of the petroleum. In the wide spectrum of fossil resources, petroleum resources run from light oils through a series of increasingly lower grade and difficult-to-extract resources (Farrel and Brandt, 2006). Unconventional resources have two properties that cause them to differ from conventional oil and result in necessarily higher greenhouse gas emissions: 1) they tend to be more difficult to extract than conventional oil, and 2) they tend to be hydrogen deficient compared to the approximately 2:1 H to C ratio present in liquid fuels . Unconventional petroleum sources include tar sands, extra heavy oil, oil shale, coal to liquid (CTL) and gas to liquids (GTL) (Greene, 2003).

Oil sands are mixtures of bitumen, water, sand and clay. The Alberta, Canada natural bitumen deposits comprise at least 85% of the world total world bitumen (Greene, 2003; Pieprzyk, Kortluke, & Hilje, 2009). The extraction of extra heavy oil currently relies on the same in situ procedures as those used in oil sand extraction. The extra-heavy crude oil deposit of the Orinoco Oil Belt, a part of the Eastern Venezuela basin, represents nearly 90% of the known extra-heavy oil in place. (Greene, 2003; Pieprzyk et al., 2009). Oil shale is formed in crude petroleum bedrock that has not yet completed the geological development necessary to form petroleum. Although oil shale has been mined and processed for more than 160 years, its economic use to date has only been possible through financial and political support (Greene, 2003; Pieprzyk et al., 2009). Coal to liquids and gas to liquids are not currently commercially produced at an industrial scale (World Coal Institute, 2009).

Natural gas conventional and unconventioal resources: Natural gas also comes from both conventional and unconventional geological formations. The key difference is the manner, ease and costs associated with extracting the resource. Conventional gas refers to the free gas trapped in porous zones in various naturally occuring rock formations such as carbonates, sandstones and siltstones. While conventional gas has been the sole focus of the industry since it began nearly 100 years ago, there has been a recent development in the exploitation of unconventional resources. The dominant unconventional natural gas is shale gas (CAPP, 2012).

Shale gas refers to natural gas that is trapped within shale formations. Over the past decade, using technologies such as horizontal drilling and hydraulic fracturing, large volumes of natural gas that were previously unavailable have become available (USEIA, 2012). There are potential environmental concerns associated with the production of shale gas, such as the great amounts of water used, potential spills and leakage of hazardous chemicals (if mismanaged) and the large amounts of wastewater generated (USEIA, 2012). Historically, the expensive production of natural gas from shale has kept its development from expanding. However, in recent years, higher prices and advances in technology have made it more profitable. There exists differences in opinion on the financial benefits of unconventional gas extraction (Urbina, 2011).

1.2 Fossil resources availability

1.2.1 Reserve estimates

Resources are of value to humans when they can be extracted and used (Udo de Haes, 2006). Economic reserve estimates serve the purpose of identifying how much resources are available for extraction. These estimates are made based on geologic and engineering data and the interpretation of this data (Society of Petroleum Engineers, 1997). Reserve estimates therefore rely on the integrity, skill and judgment of the evaluator and are affected by geological complexity and availability of data (SPE, 1997). Fossil resources reserve estimates therefore involve uncertainty. The level of uncertainty of reserve estimates is expressed by dividing reserves into two principle classifications- proven (or proved) reserves, and unproven (or unproved) reserves. The most commonly accepted definitions are based on those approved by the Society SPE (1997), presented below.

Proven reserves are those quantities of reserves that are estimated with reasonable certainty to be commercially recoverable under current economic conditions and operating technologies. There should be at least a 90% probability that these quantities will be recoverable. Proven reserve estimates are also referred to as 1P estimates.

Unproven reserves are based on geologic and/or engineering data similar to that used in estimates of proven reserves, but technical, or economic uncertainties preclude such reserves as being qualified as proven reserves. Unproven reserves are further classified as probable reserves and possible reserves.

Probable reserves are those unproven reserves, which according to analysis geological and engineering data have more than 50% chance of being recoverable. In this context, there should be at least a 50% probability that the quantities recovered are equal or exceed the sum of estimated proven plus probable reserves (also referred to as 2P estimates).

Possible reserves are those unproved reserves which according to analysis geological and engineering data are less likely to be recovered than probable reserves. In this context, there should be at least a 10% probability that the quantities actually recovered will equal or exceed the sum of estimated proved plus probable plus possible reserves (also referred to as 3P estimates).

Historically, 1P estimates have been revised upwards over time and 3P estimates have been revised downwards to converge at the estimated 2P estimate (Owen, Inerwildi, & King, 2010). For this reason, 2P estimates represent actual fossil resource reserves more accurately (Mitchell, 2004; Bentley, Mannan, & Wheeler, 2007).

It is important to note that the basis of definition for proven and unproven reserves is economic feasibility and technology availability and therefore once a reserve is deemed economical to exploit it is added to the estimate, regardless of whether it is conventional or unconventional.

1.2.2 Fossil resource reserves references

Proven reserves estimates are available from multiple databases. The data used for proven reserves in this study are those presented by BP Statistical Review (2012). These values are cross-checked with those from the IEA world energy outlook (International Energy Agency, 2012) and the USEIA International Energy Outlook (USEIA, 2012). For unproven reserves, only one database is found in the literature, namely the 2010 World Energy Council's Survey of Energy Resources (WEC, 2010). This unique document, prepared triennially, is highly regarded as a credible reference for governments, industry, investors, NGOs and academia (WEC, 2010).

Tables 4, 5 and 6 present the global proven, possible and probable reserves for petroleum. As explained in the previous section, 2P reserves are found to be more representative of fossil resource reserves availability. In Tables 1, 2 and 3 in Appendix 1, 2P reserves estimates are presented for different countries for petroleum, coal and natural gas, respectively.

Table 4 - Proven, probable and possible reserves of petroleum

	Proved Reserves (million barrels) **Source: BP (2012)**	**Probable reserves (million barrels)** **Source: WEC (2010)**	**Possible Reserves (million barrels)** **Source: WEC (2010)**
World Total	1,526,300	301,324	4,598,129

Table 5-World proven, probable and possible coal reserves (source)

	Proven Reserves (million tonnes) **Source: BP (2012)**	**Probable reserves (million tonnes)** **Source: WEC (2010)**	**Possible reserves (million tonnes)** **Source: WEC (2010)**
World Total	860,936	188,784	1,087,473

Table 6 - World Proven, probable and possible natural gas reserves

	Proven Reserves (billion cubic meters) **Source: BP (2012)**	**Probable reserves (billion cubic meters)** **Source: WEC (2010)**	**Possible reserves (billion cubic meters)** **Source: WEC (2010)**
World Total	187,100	5,520	12,508

1.2.3 Fossil resources geography and global energy markets

World oil reserves are distributed unevenly across the globe. Almost 80 percent of the world's conventional petroleum reserves are situated in eight countries, five of which are located in the Middle

East (IEA, 2012). However, the petroleum market is considered to be globally integrated. The costs of transporting petroleum are low, crude oils of different geographic regions are largely interchangeable, and regardless these different crudes can be blended (Nordhaus, 2009). This means that a shortfall in one region can be made accommodated shipping the same or similar oil from elsewhere in the world. Nordhaus (2009) examined weekly oil prices for 31 crude oils across the world and found that all oil prices fluctuated synchronically (their median correlation over the period was 0.997), indicating a true globally integrated market.

Natural gas reserves are not equally present across the globe. In fact, Russia alone posesses a quarter of the world's natural gas reserves, followed by Iran (15.7%) and Qatar (13,4%). The remaining half of the world's natural gas reserves are spread sporadically across the globe (BP, 2011). Natural gas is used mostly locally in the vicinity of the producing country. In 2011, 80% of the natural gas produced had been used in the producing country (BP, 2011), the remaining being exported through pipelines. Because natural gas is exported in pipelines, the travelling distances are much shorter than that for oil or coal. This means that the potential for a global market for natural gas is limited.

In evaluating whether coal should be considered a global or regional resource, the international trade of coal was studied. It was observed that the amount of coal traded in 2011 accounted for only 16% of the total coal consumed, as most is still used in the country in which it is produced (WEC, 2010; BP, 2011). The coal trade routes demonstrate that even the portion that is exported is not available to a global market, as transportation distances limit the economic feasibility of exporting coal (BP, 2011).

1.3 Fossil resources depletion

> *"Abiotic resource depletion is the decrease of availability of the total reserve of potential functions of resources, due to the use beyond their rate of replacement*." Van Oers et al, 2002

While fossil resources become more and more scarce, the global use of fossil resources continues to increase. Our use of fossil resources has increased 12-fold over the past 100 years, to meet the ever-increasing global demand (UNEP, 2011; USEIA, 2011). It is estimated that between 2013 and 2030, overall world petroleum production will increase by 31 percent, overall world natural gas production will increase by 52 percent, and overall world coal production will increase by 50 percent (USEIA, 2011). Global fossil resources are being depleted as a consequence.

The debate over the depletion of fossil resources is generally framed within two extremes, namely the "pessimist" and "optimist" views (Greene, 2003; Farrel et al., 2006; Brandt, 2010). The pessimists, who place their main focus on geology, foresee an imminent peaking of world oil production, leading to a "not-so-bright" future (Deffeyes, 2009). The "optimists" on the other hand focus on the economy and expect innovation and market forces to make the question of fossil resources depletion irrelevant for the world.

In between these two extreme viewpoints, there exists a more moderate view - which we call the "realist" view. The realists believe that the most promising avenue for understanding oil depletion lies in integrating the economic (i.e. resource substitution, changes in prices, changes in demand) and physical (e.g. resource depletion) factors of fossil resources production (Greene, Hopson, & Li, 2006; Brandt, 2010). According to this perspective, as conventional fossil resources diminish, there is a gradual shift to unconventional sources, and shifts to alternatives, and changes in production and prices, leading to environmental and economical impacts on the society.

Given the pertinence of the depletion of fossil resources, a series of tools and indicators have been developed to model and quantify the state of fossil resources depletion. Using this information, governments can identify the strategies required to manage resources use. These tools are explained below.

1.3.1 Prediction tools for modeling fossil resource depletion

Quantitative understanding of fossil resources depletion has increased significantly over the last century (Brandt, 2010). The first calculations of the exhaustion time of oil reserves were performed in the early 1900s. In the 1950s and 1960s, curve-fitting techniques were used to predict future production and prices. Following the 1970s oil crisis, economists became interested in the prediction tools used to forecast future prices and production. Today, hybrid simulation models are available which incorporate geological or other non-economic factors with economic ones. Each model has its advantages and disadvantages. In the following sections, the three types of prediction models that have been used in the course of this research are presented.

1.3.1.1 Reserve to production models (R/P) models

The simplest models for predicting future oil availability are reserve to production (R/P) models. These models calculate the number of years until exhaustion by dividing an estimate of current reserves by current production (Brandt, 2010). R/P models are simple to understand and simple to explain and they provide an initial indication of resource availability and the level of scarcity. The BP Statistical Review (BP, 2011) utilizes R/P values as the indicator for predicting the future availability of fossil resources.

1.3.1.2 Hubbert's logistic model, and other curve-fitting models

Curve fitting models predict the future of production and prices by fitting mathematical curves to historical data. In 1956, Hubbert predicted that US oil production would peak between 1965 and 1970. This prediction, initially a hypothesis (Deffeyes, 2009), was translated into mathematical terms in 1959: he fitted the logistic function to cumulative oil discoveries, he extrapolated the curve to find the asymptote of cumulative discoveries. A variety of Hubbert-like, curve-fitting models exist, and have been used to predict the production of fossil resources globally (Brandt, 2010). In Greene's model (Greene, 2003), prices are modeled as a logistic function of depletion in which an increase in production costs occur as a consequence of the resource becoming more scarce. The benefit of curve-fitting models is their simplicity. Due to this simplicity, curve-fitting models are a useful tool for first order projections of future production and prices (Brandt, 2010).

1.3.1.3 Energy simulation models

Energy simulation models predict the future of energy production and prices by taking into account both the economic and physical factors of energy production. We do not live in a substitution *or* depletion world, but a substitution *and* depletion world. By segregating the energy economy into sectors (such as residential, transportation, industrial, commercial, electricity) these models take into account the functions provided by energy carriers, allowing for substitution between energy carriers that provide similar functions. Simulation models offer another very appealing feature: they do not impose exogenous requirements on the shape of the production over time, but instead allow the curve to be generated through the interaction of economic and physical factors of energy production. They are used for various purposes, from forming policy to studying the effects of introducing new energy resources to the market (USEIA, 2011). Simulation models are used frequently to make medium to long-term energy projections both regionally and globally. They are used to produce energy outlooks, which are forecasts made by various agencies and companies for the future of energy (USEIA, 2011, IEA, 2011, BP, 2011). Examples of energy simulation models include World Energy Model (WEM) developed by the International Energy Agency (IEA, 2011), Prospective Outlook on Long-term Energy Systems model (POLES) developed by the Institute of Energy Policy and Economy (Enerdata, 2009), and World Energy Projection System Plus (WEPS+) developed by the United States Energy Information Administration (USEIA, 2011). WEPS+, the model used in this research, is explored further in the subsection below. The reasons for choosing WEPS+ are explained in the methodology section.

World Energy Projection System Plus (WEPS+)

The World Energy Projection System Plus (WEPS+) is an energy modeling system, produced by the United States Energy Information Administration (USEIA), and used to produce their annual International Energy Outlook report (USEIA, 2011). WEPS+ uses a database of energy data, energy models that represent the various sector-demand, sector transformation and sector supply projection, and a control system that keeps track of the models and data and executes the models . The core models used in WEPS+ are presented in Table 7. WEPS+ uses an integrated iterative process that allows for the convergence of consumption and prices.

Table 7 - WEPS+ Core Models

Type of Activity	**WEPS+ Model**
	1. Macroeconomic Model
Demand Models	2. Residential Model
	3. Commercial Model
	4. World Industrial Model
	5. International Transportation Model
Transformation Models	6. World Electricity Model
	7. District Heat Model
Supply Models	8. Petroleum Model
	9. Natural Gas Model
	10. Coal Model

	11. Refinery
	12. Greenhouse Gas Model
	13. Main Model

The flowchart presented in Figure 1 presents the sequence in which the core models are run. Each of the core models is run independently, but reads and writes to a common shared database in order to communicate with the other models. Each model completes its execution before the next model in sequence. At the end of the run, if the system does not converge, it begins another iteration. If it does converge, it ends by report writing.

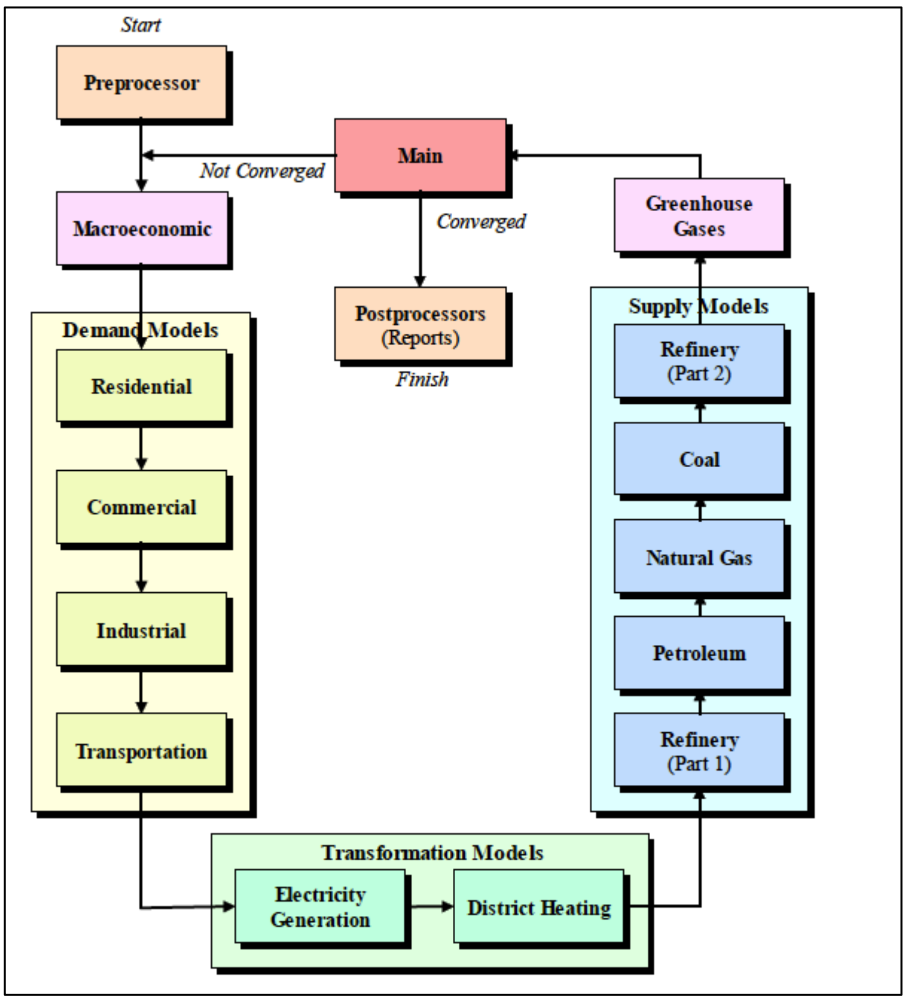

Figure 1 - WEPS+ model sequence

WEPS+ produces projections for 16 regions of the world, including North America, OECD Europe, OECD Asia, Africa, Russia, other non-OECD Europe and Eurasia, China, India, other non-OECD Asia, Brazil, and the remaining Central and South American countries. The projections extend to 2035. The WEPS+ platform is designed to allow the various individual models to communicate with each other through a common, shared database and provides a comprehensive series of output reports for analysis. In WEPS+, the end-use demand models (residential, commercial, industrial and transportation) project consumption of the key primary energy sources. For more information on how the WEPS+ model operates, the reader is referred to the documentation available on the WEPS+ model (USEIA, 2011).

1.3.2 Tools and Indicators for the assessment of the environmental impacts of fossil resource extraction and use

In order to assess the environmental impacts associated with the depletion of fossil resources, a series of indicators have been developed and used by environmental experts. *Material flow accounting and analysis (MFA)* is an approach which focuses on the concept of material and energy balancing, and calculates the domestic extraction of resources, as well as physical imports and exports (Graedel, 2003). It is used at a global, national, or regional scale. Using MFA, indicators such as mass units related to GDP (Steinberger et al., 2010), domestic material consumption (DMC), and total material consumption (TMC) (OECD, 2008) are calculated for economies, already used by the EU to calculate indicators for "Sustainable Consumption and Production" (EUROSTAT, 2007).

The concept of "Material Input per service unit" (MIPS), developed by the Wuppertal Institute for Climate, Environment and Energy (Ritthoff et al., 2002) aims at illustrating the direct and indirect energy, material, water and air inputs required along the whole life cycle of a product, from cradle to grave, to be used as a measure for resource productivity, in the effort of dematerializing the economy.

Life cycle assessment (LCA) is a standardized method that allows the assessment of the direct and indirect environmental impacts along a product's life cycle from cradle to grave (ISO, 2005a, 2005b). Since the development of LCA in the early 1990s, the impacts from resource use have been an integral part of LCA (Udo de Haes, 2006). For resources, the LCA model allows the user to determine all of the natural resources that are used throughout the lifecycle of a product or service, from extraction to production throughout use and disposal. Using life cycle impact assessment (LCIA) which is an integral part of LCA, one can identify the impacts associated with the depletion of natural resources. LCA is further explored in the following section.

1.4 Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a tool for assessing the potential environmental impacts throughout a product's life cycle, from raw material acquisition through production, to use, to end-of-life treatment and disposal (i.e. cradle-to-grave) (Finnveden et al., 2009). Life cycle assessment is still a young science, mainly developed from the mid-1980s until present day. In the 1990s, through consecutive international workshops, LCA was well-developed and a consensus was reached on the framework, leading to ISO standardization (ISO, 2005a, 2005b).

There are four phases in an LCA study: The goal and scope definition phase, the inventory analysis phase, the impact assessment phase and the interpretation phase. The four phases are displayed in Figure 5 and explained below using ISO standards definitions (ISO, 2005a, 2005b).

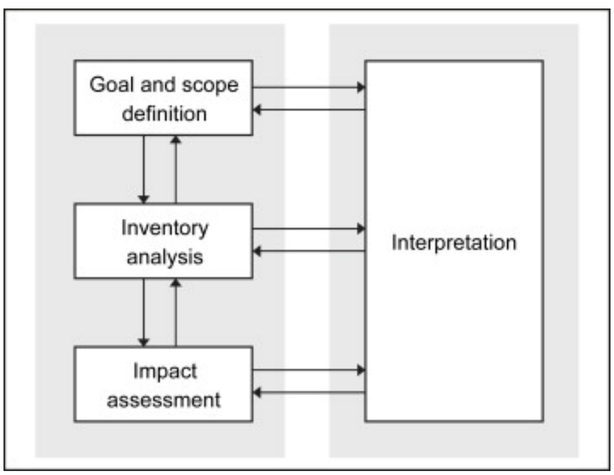

Figure 2 – Phases of LCA (ISO, 2005a, 2005b)

The first phase, *goal and scope definition*, serves to define the purpose and extent of the study, and contains a description of the system studied. At this stage, an important parameter is defined which is used as the basis for the comparison of different systems: the functional unit of a product or the services delivered. The second phase of LCA, *inventory analysis*, involves data collection and analysis. Data on the environmental interventions (such as emissions, land use, resource use) connected to each process in the life cycle are collected, often guided by a process flowchart. Data are obtained from producers, suppliers, and LCA databases. Data are then processed to produce an inventory of environmental interventions per functional unit. This procedure is not always straightforward. For example, for processes that have more than one output, decisions must be made about how to allocate environmental burdens to each output.

The third phase, *life cycle impact assessment* (LCIA), aims to evaluate the impacts of the environmental loads which were quantified in the inventory analysis phase. According to ISO 14044 (ISO, 2005b), there are two mandatory elements in this phase, namely *classification* and *characterization,* and three optional elements: *normalization, grouping,* and *weighting.*

The fourth phase of LCA, *interpretation*, evaluates the study in order to provide recommendations and conclusions. LCA is seen as an iterative process and interpretation can often times lead to an adjustment of the goal and scope or to further investigations of the inventory and associated impacts (ISO, 2005a).

Attributional versus consequential LCA

The methodological consensus on LCA is defined in the ISO standards and often referred to in the literature as attributional LCA (ALCA). ALCA accounts for all the impacts exerted on the environment within the life cycle of a product. ALCA therefore only describes the physical flows associated with the potential environmental impacts that are directly linked to the product system (Ekvall & Weidema, 2004).

It should be noted that certain environmental impacts caused by product changes may occur outside the product life cycle. For this reason, a new form of LCA, referred to as consequential LCA (CLCA), has been developed (Ekvall & Weidema, 2004; Earles & Halog, 2011). Unlike ALCA, consequential LCA (CLCA) describes the impacts of a decision and all processes and material flows that are directly or indirectly affected by a marginal change in the output of a product through market effects, substitution, use of constrained resources, etc. Additionally, allocation is avoided by system expansion. CLCA is a more complete type of assessment, since it takes more than the studied life cycle into account and examines how the environmental impacts are affected when the state is changed. CLCA considers the market effects of a product's production and consumption and has broader applications than ALCA, such as public policy making, social action plans and product development.

While CLCA began with simple economic tools, increasingly sophisticated methods have been developed (Ekvall & Weidema, 2004; Baumann & Tillman, 2004). Initial efforts have relied on simple partial equilibrium models for predicting affected technologies and more recent models have incorporated sophisticated economic models for this purpose. As an example, the Global Trade Analysis Project (GTAP) has been used to determine the affected technologies across the global economy (Dandres et al., 2012). While global economy models such as GTAP provide a more comprehensive output with respect to the number of regions and sectors included, they have been criticized for their low product sector resolution (Earles & Halog, 2011).

1.5 Life Cycle Impact Assessment (LCIA)

As the focus of this research is on LCIA, it is further explored in the section below. In this section, the state-of-the-art methods for LCIA of fossil resources, and their strengths and weaknesses are explored.

Life cycle impact assessment (LCIA), aims to evaluate the impacts of the environmental loads which were quantified in the inventory analysis phase of an LCA. The main purpose of the LCIA is thus to turn the inventory results into more environmentally relevant information, i.e. information on the impacts to the environment, rather than just information on emissions and resource use. Another purpose, perhaps often less stated, is to aggregate the information from the life cycle inventory (LCI) into fewer parameters (Baumann & Tillman, 2004)

According to ISO 14044, there are 2 mandatory elements, namely *classification* and *characterization,* and 3 optional elements, *normalization, grouping,* and *weighting* (ISO, 2005b).

In *Classification*, the elementary flows, which are flows directly to or from the natural environment (including resource consumption, emissions to air, water and land, etc.) are assigned to impact categories according to each flow's ability to contribute to the different environmental impacts. In Figure 3, the impact categories recommended by the ILCD handbook (ILCD 2010a, 2010b) are presented.

In *characterization*, the impact of each elementary flow is modeled quantitatively according to the environmental mechanism. An *impact pathway*, which is a series of phenomena that link the elementary flows to impacts on the Areas of Protection (AoPs) is defined. An indicator is chosen to represent the impact caused by the elementary flow. According to ISO 14044, this indicator can be chosen anywhere along the impact pathway. *Midpoint indicators* are parameters that indicate the impacts somewhere along, but before the end of, the impact pathway. *Endpoint indicators* are parameters representative of the impacts all the way to the end of the impact pathway, and on the Areas of Protection (AoPs) (Bare et al., 2002).

In order to convert environmental interventions into impacts, *characterization factors* (CFs) are used. Characterization factors are estimated using characterization models which are simplified mathematical representations of the biophysical processes which occur throughout the impact pathway.

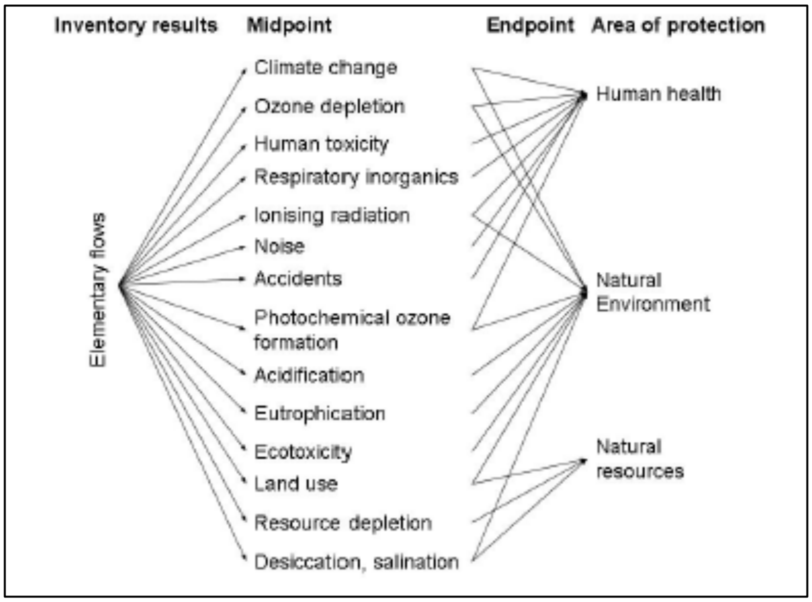

Figure 3- Framework of impact categories for characterization at midpoint and endpoint (Area of Protection) levels.

LCIA is a discipline undergoing active development. Several LCIA methods are available and there is not always an obvious choice between them. In spite of the resemblance between some of the methods, there can be important differences in their results each produces, that can lead to conclusions which vary depending on the choice of the LCIA method (Dreyer et al., 2003). In the following section, a review of the existing LCIA methods for fossil resource depletion is presented. Methods that are related to the scope of this research are explored in more detail.

1.5.1 A review of the existing LCIA methods on the characterization of fossil resource depletion

While there hasn't been a standardization attempt from ISO for LCIA methodologies to date, various studies have aimed at evaluating existing methods and making recommendations. The UNEP/SETAC life cycle initiative was an attempt to identify best practices for Life Cycle Assessment within the ISO framework. These efforts led to a publication (SETAC, 2003) reporting on best practices. More recently, the European Commission, in consultation with several non-EU countries, has taken a major step in further facilitating the development of formal international recommendations for LCIA through the International Reference Life Cycle Data (ILCD) System, leading to three publications that analyze the existing LCIA methods, make recommendations, and provide evaluation criteria for future methods (ILCD 2010a, 2010b, 2011). The common impact pathway that is used by these methods is presented in Figure 4. The ILCD has divided existing LCIA methods for fossil resources depletion into three groups:

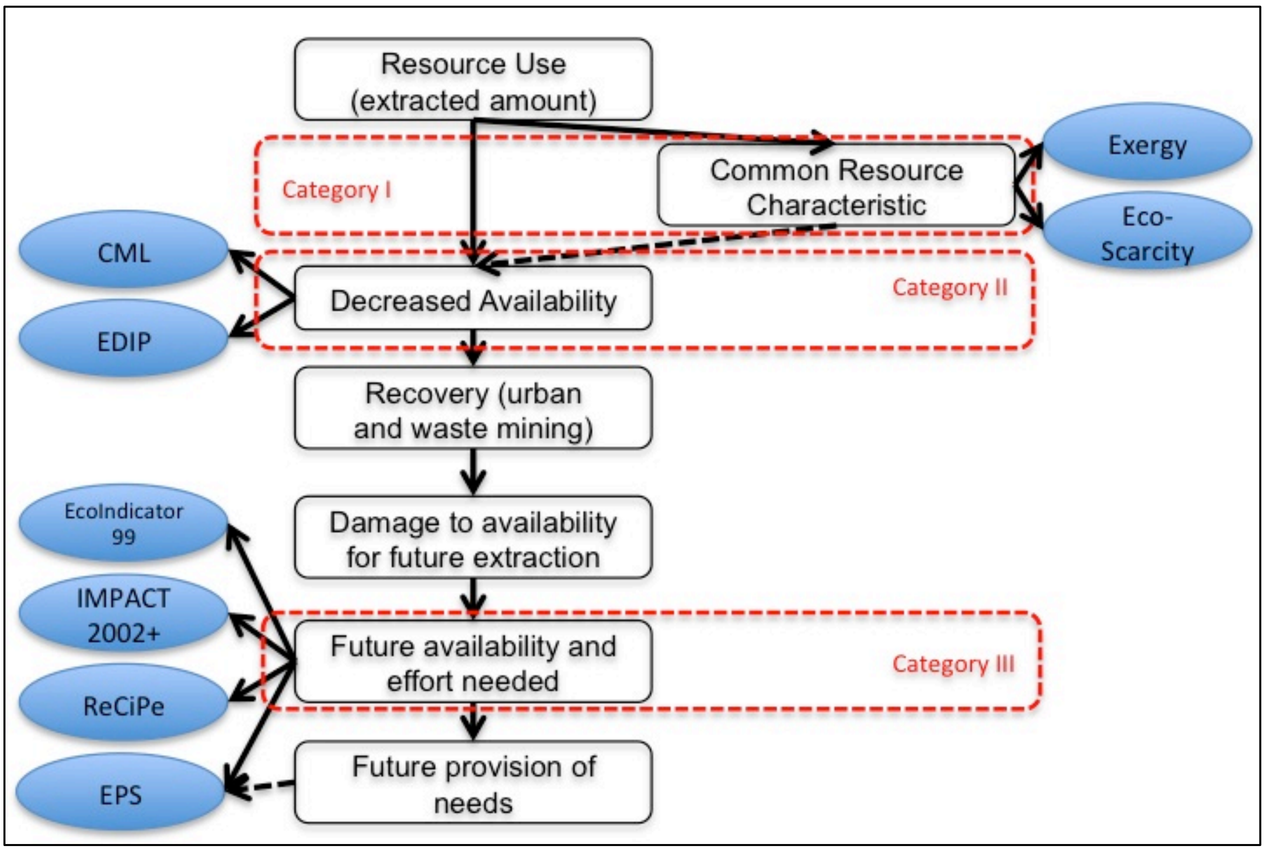

Figure 4 - Impact pathway used by existing LCIA methods for fossil resources depletion

Category I methods use an inherent property of the material (such as mass or exergy) as a basis for characterization (Bosch et al., 2006; Dewulf et al, 2007). The most developed method in this category is exergy. Exergy is the potential of a system to cause change as it achieves equilibrium with its environment, with units of Joules. Exergy analysis is performed in industrial ecology to make energy use more efficient. In resource use characterization for LCA, a recent approach based on exergy is published by (Dewulf et al., 2007). This method quantifies the exergy values taken away from natural ecosystems for numerous resources including fossil fuels, minerals, nuclear energy, land resources, renewable resource, atmospheric resources and water resources. Recent advancements have enhanced these approaches and the ILCD report considers the scope of the exergy method complete. The strength of this indicator its relatively low uncertainty levels (ILCD, 2011), however this method has been criticized for not reflecting the scarcity of the resources in LCA. Regardless of the scarcity of the resource, the exergy value remains the same (Stewart & Weidema, 2005; Finnveden et al, 2009).

Category II methods address resource scarcity and decreased availability. This group of methods focus on measures of deposits and consumption rates. They have a higher environmental relevance, but also have the potential to have a higher uncertainty compared to the first group. Methods that fall into this category include EDIP (Dreyer et al., 2009; Finnveden et al., 2009) and CML 2001 (Van Oers et al., 2002).

Category III methods describe the endpoints, aiming to cover the entire environmental mechanism. Methods in this category include EcoIndicator 99, Impact 2002+, ReCiPe, and EPS 2000.

The LCIA methods presented in Figure 4 are listed in table 8. In this table, the origin of the methods and the characterization method is presented. The references for further reading for each LCIA method are also presented.

Table 8 - LCIA methods for fossil resource depletion mentioned in the ILCD reports

Method	**Developed by**	**Characterization method**	**Reference(s)**
Exergy	Dewulf, 2007	Exergy (MJ Exergy/MJ)	Bosch et al., 2006 Dewulf et al., 2007
Swiss Eco-Scarcity	E2 + ESU, Switzerland	Net Calorific Value (HHV) (MJ/MJ)	Frischknecht, 2007
CML 2001	CML Netherlands, 2002	Abiotic depletion potential (kg $_{Sb\ eq.}$ /MJ)	Van Oers et al., 2002
EDIP 97	DTU Denmark,	person-reserve (person-eq./ MJ)	Dreyer et al., 2009 Finnveden et al, 2009

EcoIndicator 99	Pré Consultants, Netherlands	Surplus energy (MJ surplus/MJ)	Goedkoop & Spriensma, 2000
Impact 2002+	EPFL Switzerland	Surplus Energy (MJ/MJ)	Jolliet et al., 2003
ReCiPe	RUN + Pré + CML + RIVM Netherlands	Total Additional Costs ($/MJ)	Goedkoop et al., 2009
EPS	Chalmers University, Sweden	Willingness to pay (ELU/person)	Steen, 1999

In the sections below, a selection of methods both related to the scope of this research and which are recommended by the ILCD handbook are further explored.

1.5.1.1 CML 2002

CML 2002 is an LCIA methodology based on the work of Guinee and Heijungs (1995). CML 2002 characterizes the impacts associated with the depletion of fossil resources using the abiotic depletion potential (in MJ fossil energy).

In their methodology, Guinee and Heijungs (1995) suggest that the *ultimately extractable reserve* is the only relevant reserve parameter in terms of depletion. However since data on this type of reserve is unavailable and dependent on future technology, it is proposed to use the *ultimate reserves*. Ultimate reserves are estimated by multiplying the average concentrations of chemical elements in the earth's crust by the mass of the crust. For fossil fuels, a rough estimate of the ultimate reserves is made on the basis of the *fossil carbon* content of the earth's crust.

In CML 97 the above values for ultimate reserves are used to calculate the abiotic depletion potential (ADP) separately for each fossil fuel. In CML 2002 however, fossil fuels are assumed to be full substitutes (both as energy carriers and as materials), so their abiotic depletion potential (ADP) is taken as the same in terms of total energy reserve. The abiotic depletion potential is defined as:

$$ADP_{fossil\ energy} = \frac{deaccumulation\ rate_{fossil\ energy}}{\left(Ultimate\ reserve_{fossil\ energy}\right)^2} \times \frac{\left(Ultimate\ reserve_{antimony}\right)^2}{deaccumulation\ rate_{antimony}}$$

where the ADP is the abiotic depletion potential of fossil fuels (in kg antimony eq./MJ fossil energy), the ultimate reserve of fossil fuels is in MJ, the de-accumulation, or fossil energy production is in MJ/yr. The ultimate reserve of antimony, the reference resource, is presented in kgs. The de-accumulation of antimony, the reference resource is in kg/yr.

Fossil resource	**Characterization factor**	**Unit**
Energy from coal	4.57E-04	$kg_{sb\ eq.}$/MJ
Energy from natural gas	5.34E-04	$kg_{sb\ eq.}$/MJ
Energy from petroleum	4.90E-04	$kg_{sb\ eq.}$/MJ

1.5.1.2 EDIP 97

EDIP 97 assesses the impacts for resources at midpoint level by (1) multiplying extraction by the annual production and dividing the result by the economic reserve, and (2) dividing the result again by the annual production. Characterization factors are expressed in person-reserves. A person-reserve is the quantity of a resource available to the average world citizen if the world's economic resources were equally shared by the world population. Economic reserves are defined as resources that can be extracted in an economically feasible way using today's technology.

Fossil resource	**Characterization factor**	**Unit**
Energy from coal	4.56E-07	Person-reserve/MJ
Energy from natural gas	1.40E-06	Person-reserve/MJ
Energy from petroleum	49.56E-07	Person-reserve/MJ

1.5.1.3 Criticism of Midpoint indicators

Although there are minor differences in the LCIA method for CML 2003 and EDIP 97, they share a similar approach by using a fraction of available reserves over production rates. As it was explained in section 2.2, reserves to production (R/P) rates are a simple way of explaining resource availability.

As explained in section 1.2.3, although the market for petroleum can be considered global, coal and natural gas reserves are not completely shared by the world. Considering global values for reserves over production rates is not therefore a correct assumption. A more accurate characterization would be to look at each country's supply mix of the resource and consider the scarcity in each country.

Considering the full substitutability of all fossil resources is not a correct assumption. Although for some applications, substitutability is possible (e.g. natural gas can replace coal in electricity production, subject to availability), for many applications, fossil fuels cannot be replaced e.g. coal will not be used for vehicle transportation because of low energy to weight ratio. When considering substitution, the application for which the fossil resource is being used for should be accounted.

The ultimate resource base (used as default in calculations of depletion in the CML 2002 method) is a relatively robust reference with low uncertainty, but its environmental relevance seems limited. It leads to problems with underestimating the severity of depletion. Using economic reserves has higher uncertainties because it is subject to change, but is more representative of the actuality of the available resources. The ILCD therefore recommends that these two extremes can be used as guides to assess the severity of the impacts associated with the use of a resource (ILCD, 2011).

1.5.1.4 ReCiPe

ReCiPe is an LCIA methodology that characterizes the impacts associated with using fossil resources at endpoint as the consequential reduction in the quality of remaining resources, resulting in increases in production costs as mankind will have to switch from conventional resources to unconventional resources (Goedkoop et al, 2009). At endpoint, ReCiPe characterizes the impacts based on the increase in cost of resource extraction as a consequence of depletion (marginal cost increase). The impact at endpoint is defined as the total additional costs that the society will have to bear in the future due to the marginal cost increase.

Fossil resource	Characterization factor	Unit

Energy from coal	0.382	$/MJ
Energy from natural gas	0.382	$/MJ
Energy from petroleum	0.382	$/MJ

1.5.1.5 Criticism of Endpoint indicators

ReCiPe relies on the assumption that the earth's available resources are being extracted in an orderly fashion, i,e, the highest quality ores/resources are being extracted first. This is certainly not the case with fossil fuels, where extraction of unconventional resources and production of alternatives has already begun. An example is the current extraction of oil offshore and from resources such as bitumen etc.

ReCiPe does not address the elasticity that exists in the real world between an increase in prices and changes in demand. A marginal increase in the price of the resource in a real world situation can lead to partial changes in the demand of the resource.

The ILCD report states that at endpoint level, all methods evaluated are too immature to be recommended. The ReCiPe method is the recommended interim method by the ILCD for abiotic resources at endpoint level, only for in-house applications (ILCD, 2011).

1.5.1.6 The functional perspective in LCA

The functionality perspective towards resource use has initially been investigated by Stewart and Weidema (2005). According to the functionality perspective, resources are valued for the functions that they provide to the society, not their mere existence. Based on this perspective, in studying resource depletion, the functions that a resource provides to the society should be considered, and transitions to future technologies /resources that provide the same functions should be taken into account. Stewart and Weidema's view on fossil resources is that the transition to future technologies should be modeled as a part of the inventory analysis. It is also agreed that the economic and social impacts of resource use need to be addressed as well (Finnveden, 2005). Similar ideas have briefly been proposed in the past. In Ecoindicator 99 (Goedkoop and Spriensma, 2000), the necessity of addressing substitutes in future methods is stated.

The functionality concept has been used for the definition of an LCIA methodology for water use (Bayart et al., 2010; Boulay et al., 2011), In this approach, the value of freshwater as a resource has been associated with the functions that it delivers in the technosphere. The functionality concept has been used for the definition of an LCIA methodology for water (Boulay et al., 2011. Bayart et al. explain that when freshwater availability is reduced, two scenarios are possible: deficiency and compensation. The choice between deficiency and compensation scenarios is based on socioeconomic parameters. The compensation scenario, possible through backup technologies, is made possible by expanding the product system boundaries to include the environmental burdens generated by the backup technology chosen. These rebound effects are considered in the LCI (Finnveden, 2005).

1.6 Significance of fossil resource depletion in LCA

To put into perspective just how much of the environmental impacts are attributed to fossil resource use in LCA studies, a case study was performed.

A numerical review was performed on current LCIA methods, where the characterization factors of fossil resources were compared to characterization factors of some selected metals. In order to perform a comparison, some abundant metals (Iron, copper, aluminum, nickel) and some rare and precious metals (silver, platinum, molybdenum, gold) were chosen. The fossil resources chosen were coal (24.6 MJ/kg), Gas (35 MJ/m^3), and oil (42.6 MJ/kg). The LCIA models studied were EDIP 2003, CML 2001, EcoIndicator 99, Impact 2002+, and ReCiPe (the graphs presenting these comparisons are presented in Appendix 7). In all but one of the LCIA methods studied, the characterization factors (CFs) are of significance when compared to metals. EDIP 2003, which bases its depletion factor for fossil fuels on ultimate resources, has the lowest relative characterization factors for fossil resources, comparable to those of iron. In CML 2001, fossil resources are characterized as comparable to molybdenum, and are only two orders of magnitude less scarce than platinum. In EcoIndicator 99, fossil resources characterization factors are only two orders of magnitude smaller than the metal resource with the highest characterization factor, (tin, in ground, with a characterization factor of 600 MJ surplus/kg). In ReCiPe, fossil resources characterization are comparable to Molybdenum and silver, and are only 2 to 3 orders of magnitude smaller than those of gold and platinum, respectively. As for IMPACT 2002+, fossil resources are characterized with CFs higher than almost all metals. This is due to the inconsistency in the way abiotic resources are modeled [fossil resources have CFs based on upper heating values (MJ/kg), and metals are based on surplus energy for mining (MJ/kg)].

Characterization factors are not the only parameter that affect the overall impact score. Impact is calculated by multiplying the characterization factors by the mass (or volume) of the resource used in the process (obtained from the life cycle inventory). So it is actually important to know *how much* of a resource is used in technological processes.

In this study, seven arbitrary processes were selected, and the amounts of resources used in each process were compared (the tables are presented in Appendix 4). These include the production of a unit of concrete, aluminum alloy, sugar, paper, and an LCD monitor, and 1 tonne-kilometer of transport. It is observed that in all processes, the amount of fossil resources consumed ranks from moderate to considerably high compared to the selected metals.

Personal communication with CIRAIG analysts also confirmed that for many LCA studies, the impacts modeled using the available LCIA methods for the safeguard subject of resources are dominated by fossil resource use.

IDENTIFYING THE KEY RESEARCH NEEDS

In this section we present the key research needs that were identified based on the literature review that was presented in this chapter.

- The ILCD has reviewed and analyzed all existing LCIA methods and has concluded that at both midpoint and at endpoint, the methods developed to date have drawbacks. It has identified the development of a new model to improve the current state of fossil resource depletion impact assessment in LCA as a priority.
- The functionality approach which seeks to calculate the environmental consequences of meeting the functionalities provided by a resource, hasn't yet been explored for fossil resources though this approach has been successfully applied to other abiotic resources (IMPACT World+, 2013).
- Substitutability has not been addressed correctly in the previous LCIA models. Fossil resources provide various functions, and substitutability between energy resources should be considered in accordance with the type of use. Nuclear energy and renewables should also be considered in the energy market as alternatives to certain uses.
- Ecoinvent has released its version 3 in May, 2013 (Ecoinvent, 2013). This long-awaited update to the database features an important addition to version 2.0: there is improved regionalization for many datasets, supporting regionalized impact assessment. Ecoinvent states that it is "getting closer to its goal of providing a true reflection of global chain supplies". Regionalization has been missing from LCI databases and LCIA methodologies for fossil resources. Upon releasing a regionalized life cycle inventory database for fossil resource use, a regionalized LCIA method is required.

These identified research needs led to the definition of the hypothesis and research objectives that are presented in the following page.

RESEARCH HYPOTHESIS

The research hypothesis is defined as below:

The discriminating power of assessing the impacts of fossil resources depletion in LCA can be improved by adopting a functional approach that accounts for resource depletion in a regional manner, as well as for resource substitutability and user adaptability through energy markets modeling. This can be verified by presenting the new characterization factors for different fossil resources in different countries and comparing results with previous LCIA methods results.

RESEARCH OBJECTIVES

After identifying the key research needs, the general objective of this research is defined as follows:

The objective of this study is to develop a new LCIA methodology for fossil resources depletion using a functional perspective allowing to calculate midpoint and endpoint characterization factors and indirect impacts in a regionalized manner while accounting for resource substitutability and user adaptability.

The sub-objectives are defined as below:

1. To develop the impact assessment framework for the *depletion of fossil resources* based on the functional perspective;
2. To develop the midpoint indicator expressing the amount of resource deprived for future users as a consequence of fossil resource dissipated;
3. To develop the endpoint indicator by further modeling the cause-effect chain, linking resources depletion to the total additional costs that a society has to bear as a consequence of depleting a resource;
4. To model the indirect impact of fossil resource depletion by establishing the link between fossil resources depletion and the environmental impacts associated with the changes in the energy market as a consequence of the depletion of a fossil resource; and
5. To evaluate the obtained characterization factors.

CHAPTER 2 METHODOLOGY

The methodology section is divided into six tasks in accordance with the research objectives.

2.1 Task 1: Defining the general Framework

The impact pathway for the depletion of fossil resources is presented in figures 5 and 6.

The IMPACT World+ (IMPACT World+, 2013) framework for resources depletion is used as the foundation for the proposed work and is adapted to the context of fossil resources. The impact pathway begins with fossil resource dissipation (presented in *MJ* dissipated). In the following step, using the regionalized scarcity indicator (midpoint characterization factor named FOCSI), the amount of reduced availability of the resource for future users is calculated (presented in Mega joules deprived from future users). This parameter is selected as the midpoint indicator. In the third step, the marginal reduction in the availability of a non-renewable resource is linked to an increase in its price termed Marginal Price Increase (MPI), expressed in $/MJ per MJ deprived from future users. At the fourth step, the energy market adapts to this change in price by changes in the consumption and price of the fossil resource and also of other energy carriers as well. The adaptation of the energy market, in net present dollars, is linked to the previous parameter using TAC, the total additional costs parameters ($ per $/MJ). In the last step, in line with the IMPACT World+ framework, the additional costs that the society has to bear as a consequence of the depletion of the fossil resource are defined as the direct impacts, affecting the “resources and ecosystem services” area of protection. Resources and ecosystem services account for all the benefits that natural resources and ecosystems supply (Millennium Ecosystem Assessment, 2005). Potential impacts on this area of protection represent the costs that the society would have to pay to replace the lost or affected services. The direct impacts of fossil resources depletion is presented under the same area of protection, leading to additional costs that the society has to bear.

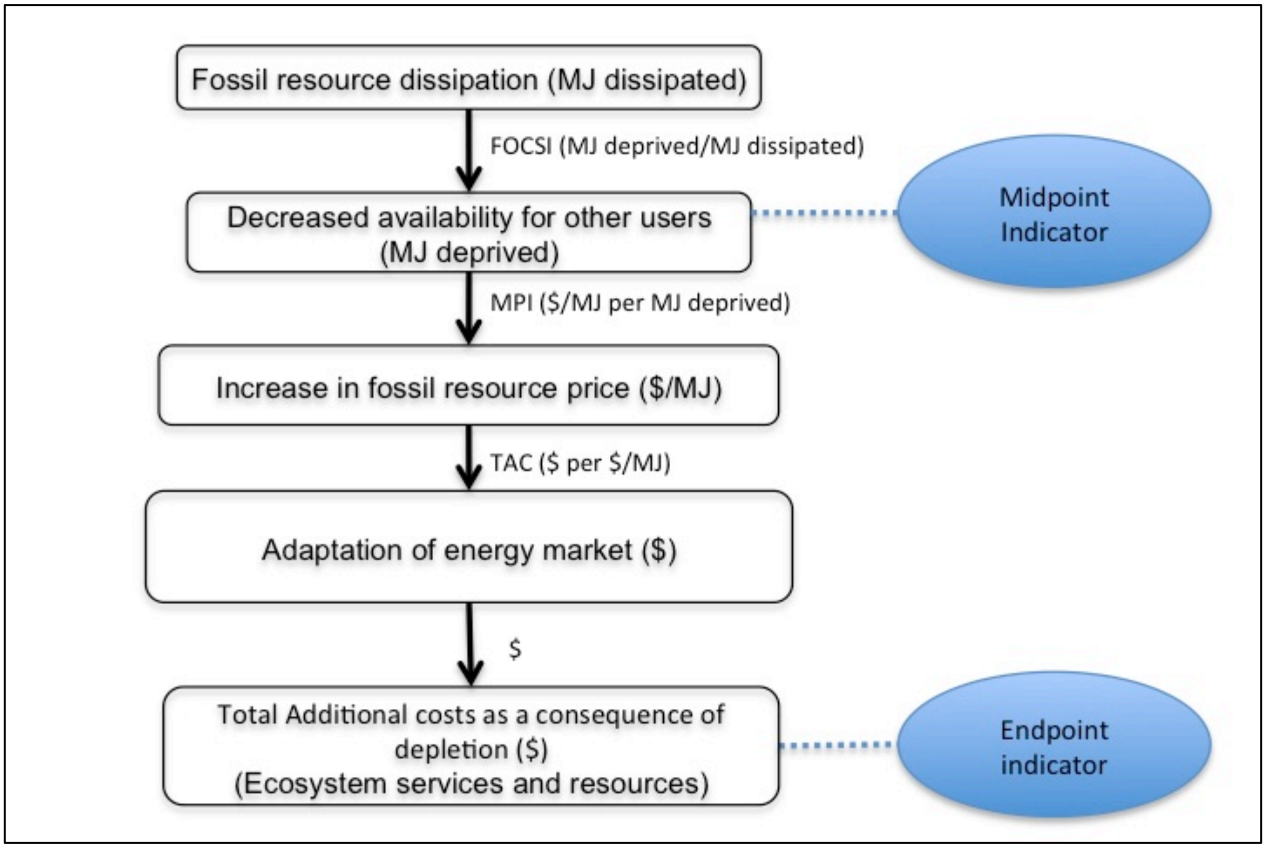

Figure 5- Impact chain for the direct impacts associated with the depletion of fossil resources

The characterization factors at midpoint for fossil resource *f* extracted in country *c* are defined as:

$$CF_{f,c}^{midpoint} = FOCSI_{f,c} \qquad \text{Equation 1}$$

where $FOCSI_{f,c}$ is the scarcity indicator for fossil resource f in country c. The units for the midpoint characterization factors are $\left(\frac{MJ\ deprived\ from\ future\ users}{MJ\ dissipated}\right)$. $FOCSI$ calculations is presented in section 2.2.

The characterization factors at endpoint for fossil resource *f* extracted in country *c* ($/ MJ dissipated) are defined as:

$$CF_{f,c}^{endpoint} = FOCSI_{f,c} \cdot MPI_f \cdot TAC_f \qquad \text{Equation 2}$$

where:

$FOCSI_{f,c}$ is the country-specific scarcity index expressed in $\frac{MJ\ deptrived\ from\ future\ users}{MJ\ dissipated}$ (explained in section 2.2);

MPI_f is the global marginal price increase for fossil resource *f*, expressed in $\frac{\$/MJ}{MJ\ deprived\ from\ future\ users}$ (explained in section 2.3);

TAC is the total additional costs as a consequence of the unit price increase for fossil resource f, expressed in $\frac{\$}{\$/MJ}$ (explained in section 2.3).

The adaptation of the energy market also leads to indirect impacts on the environment. The indirect impacts of the depletion of fossil resources are defined as the life cycle impacts of the total additional consumptions of different energy carriers. The impact pathway for the indirect impacts of fossil resource depletion is presented in figure 6.

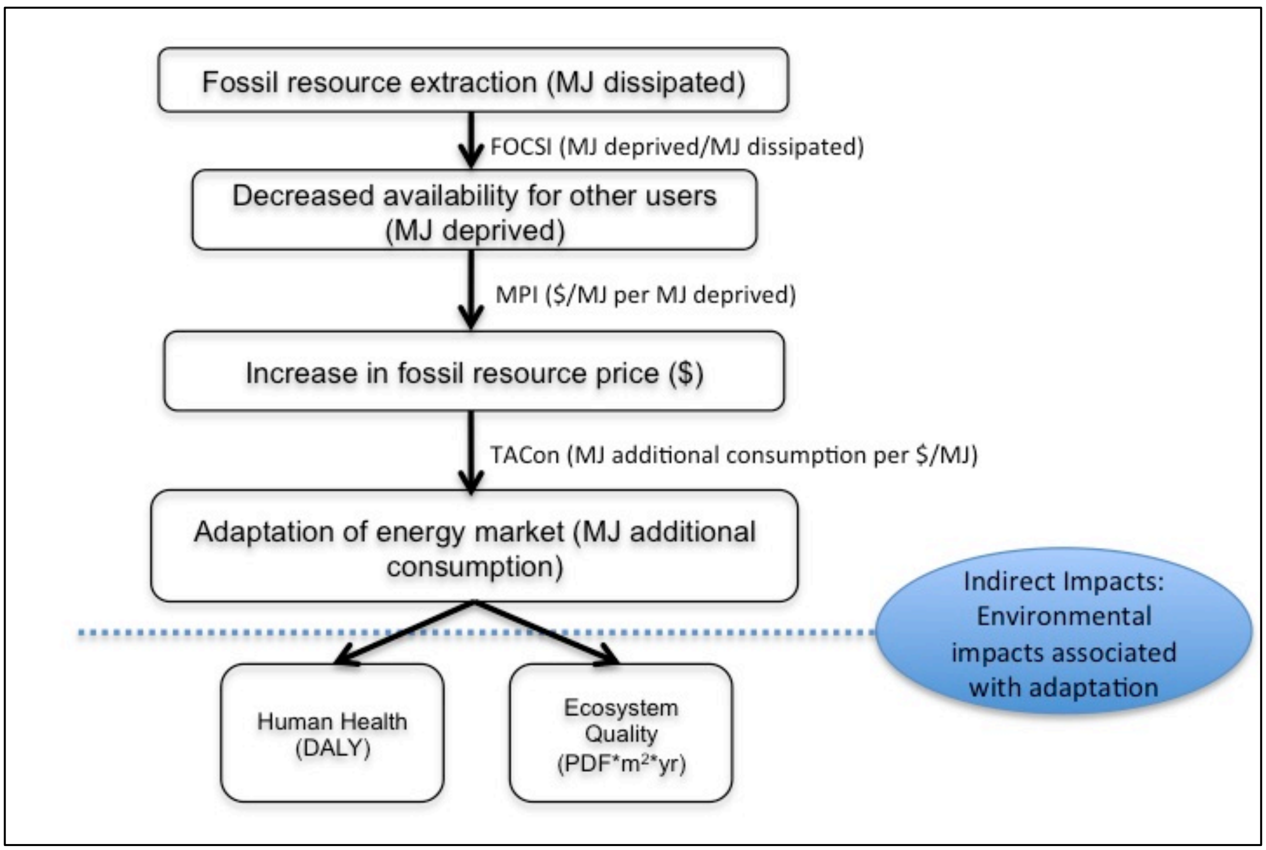

Figure 6 - Impact chain for the direct impacts associated with the depletion of fossil resources

2.2 Task 2: Developing a midpoint indicator

In this task, the midpoint characterization factor is defined, which links the extraction of a resource (and its dissipative use) to the reduction of availability of that resource for future users.

2.2.1 Defining the scarcity index

The ratio between the available reserves of a fossil resource to the annual production rates of the resource, in a particular country, is chosen as an indication for the scarcity of the resource.

The fossil resources competition scarcity index (FOCSI) is calculated as a function of reserves-over-production (R/P) values and expressed as a number between 0 and 100%, with units *Mega joules deprived from future users/ Mega joules dissipated*. FOCSI expresses a reduced availability in MJ to future users due to the extraction and dissipation of 1 MJ of the resource. FOCSI is set to zero if the resource is deemed abundant in a region, and set to one if the resource is considered very scarce. Figure 7 is a graphical representation of the FOCSI curve as a function of R/P values.

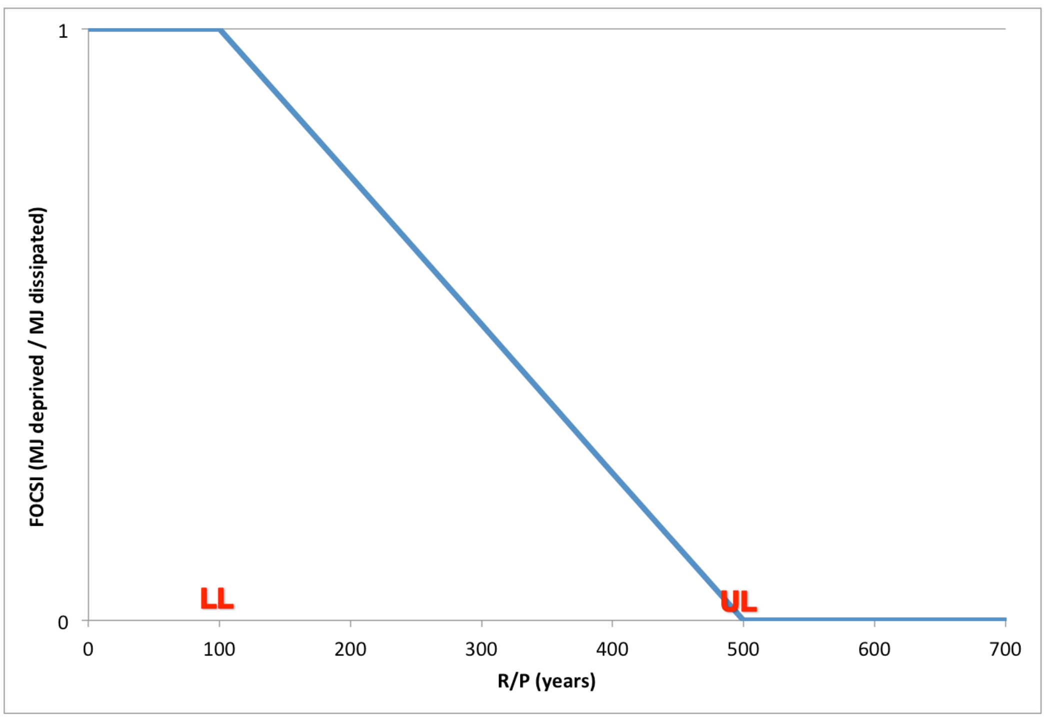

Figure 7- FOCSI plotted as a function of R/P values and the selected time horizons

A resource is considered very scarce if it has an R/P value smaller than the lower limit (LL expressed in years) (FOCSI=1). In this case, the extraction (and dissipative use) of 1 MJ of a fossil resource leads to the reduction in the availability of 1MJ of the resource for future users in the country where it is extracted. On the other hand, a resource is considered abundant if R/P values are above the upper limit (UL, expressed in years) in which case FOCSI equals zero. For reserves-to-production ratios between the LL and UL years, a linear distribution is assumed.

FOCSI values for fossil resource *f* in country *c* are therefore mathematically defined as below:

if $\left(\frac{R}{P}\right)_{f,c} \leq LL$; $FoCSI_{f,c} = 1$;

if $LL < \left(\frac{R}{P}\right)_{f,c} < UL$; $FoCSI_{f,c} = \frac{UL-\left(\frac{R}{P}\right)_{f,c}}{UL-LL}$;

if $\left(\frac{R}{P}\right)_{f,c} \geq UL$; $FoCSI_{f,c} = 0$.

Equation 3

here $R_{f,c}$ is the available reserves of fossil resource *f* in country *c*, and $P_{f,c}$ is the annual production of fossil resource *f*.

FOCSI values are selected as midpoint characterization factors. It should be noted that in calculating R/P values in the impact chain, the simplifying assumption is used that all of the fossil resource that is extracted is dissipated, and therefore does not account for the fraction that is not dissipated and can be considered anthropogenic reserves.

2.2.2 Developing the characterization factors

Historically, the natural gas and coal industry have used Higher heating values (HHV), while petroleum-derived fuel motors have ended up using lower heating values (LHV)[1] (Andrews, 2010). The lower and higher heating values, as found in Frischknecht (2007) for petroleum, hard coal, lignite, and natural gas are presented in table 9.

Lower heating values (LHV) are determined by subtracting the heat of vaporization of the water vapour from the High Heating Value (HHV). In calculating HHV one assumes that the water component is in liquid state at the end of combustion. [1]

Since HHV values are representative of the potential energy that lies in fossil resources, we use this value for calculating our total reserves and annual productions and in calculating the characterization factors for non-renewable energy consumption in terms of total energy extracted, similar to Jolliet et al. (2003) and Goedkoop et al. (2009).

Table 9-Fossil resources LHVs and HHVs (source: Frischknecht, 2007)

Fossil resource	Lower heating value (MJ/kg)	Higher heating value (MJ/kg)
Petroleum	43.2	45.8
Coal	28.6	28.9
Lignite	16.8	17.8
Natural gas	45.4 (36.3 MJ/m^3)	50.4 (40.3 MJ/m^3)

The lower and upper limits in the time horizon are chosen to be consistent with the IPCC's time horizons for climate change impact assessment (IPCC, 2006). One-hundred and five-hundred years were chosen as the lower and upper limit of the time horizon. One hundred years is roughly the time that our immediate next generation would still be present, so any resource depletes in less than 100 years is deemed scarce. 500 years is considered so far into the future that it is believed that humans will have fully relieved their dependence on fossil resources, or discovered technologies to overcome the problem of depletion. The choice of a time horizon is a crucial value choice to evaluate the importance of the reduced availability. A sensitivity analysis is conducted on the choice of the upper and lower limits of the time horizon see section 3.4.2.3.

Following the human-centric perspective in the functional approach, resources are only deemed valuable when there's the possibility of extracting them and using them. Economic reserves are therefore deemed relevant in calculating the available reserves for humans. Ultimate resources estimates reflect what is present in the earth's crust and do not reflect on the portion that is available for human use. Economic reserve estimates are therefore deemed appropriate for use in the R/P calculations.

2P (proven+probable) reserves estimates are chosen for the reserves values of a fossil resource for a particular country (see section 1.2.1). According to recent data for the last 20 years, annual production rates for all fossil resources were increasing annually, therefore the most recent annual extraction values available were used as the most conservative result. Fossil resources are predominantly used dissipatively (see sections 1.1.1 to 1.1.3) and therefore a simplifying assumption is used here that all of the fossil resource that is extracted is dissipated (extraction rate = dissipation rate). This way, we are neglecting the fraction that is not dissipated and can be considered anthropogenic reserves (such as plastics, asphalt, etc.)[2]. Where 2012 data was not accessible, the most recent data found was used. The sensitivity of FOCSI values to reserves-over-production uncertainty is investigated in task 4.

Figures 8 and 9 are a graphical presentation of R/P values (in years) for coal and natural gas by country. Countries that have no reserves are shaded in grey. In this map, countries with R/P values greater than 500 are given an R/P of 500, as their corresponding FOCSI values would be zero regardless of R/P values. For petroleum, as explained in section 1.2.3, a global market assumption is used and therefore country-specific R/P ratios are not used.

Recent technological advancements are making shale gas an increasingly important source of natural gas in the United States, and interest has spread in the rest of the world. There has been a considerable debate over the level of technically recoverable shale gas resources together with significant revisions to the estimates of some of these resources (Stevens, 2012). Reserves-over-production values can be updated accordingly using annual reserves estimates.

As seen in Figures 8 and 9, reserves over production rates vary significantly across the global for coal and natural gas. Available reserves, annual production rates and reserves-over-production rates are presented for all countries in tables 1, 2 and 3 for petroleum, coal, and natural gas in appendix 1. If a country had no reserves, it was not presented in the tables.

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[2] If anthropogenic stocks are to be accounted for, one should add them to available reserves when calculating R/P values (Schneider, Berger, & Finkbeiner, 2011) propose a methodology for accounting for anthropogenic stocks). It should be noted however that adding anthropogenic stocks (such as plastics) to the total reserves will add an additional complication as these stocks are not necessarily substitutable for all uses.

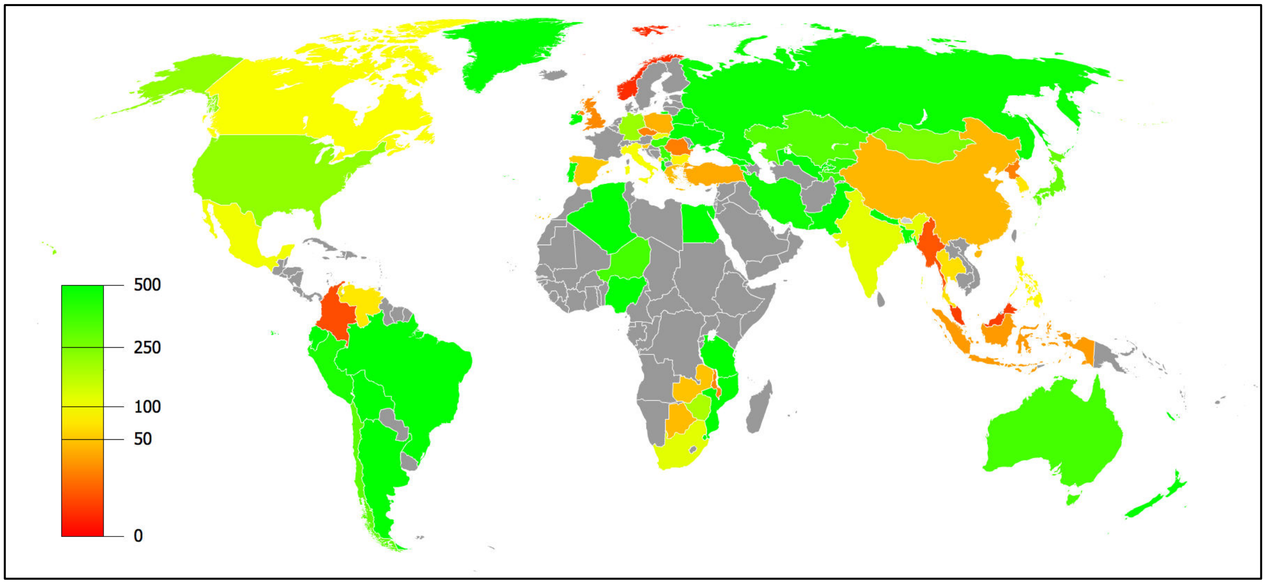

Figure 8-Reserves over production ratios (years) for coal for different countries.

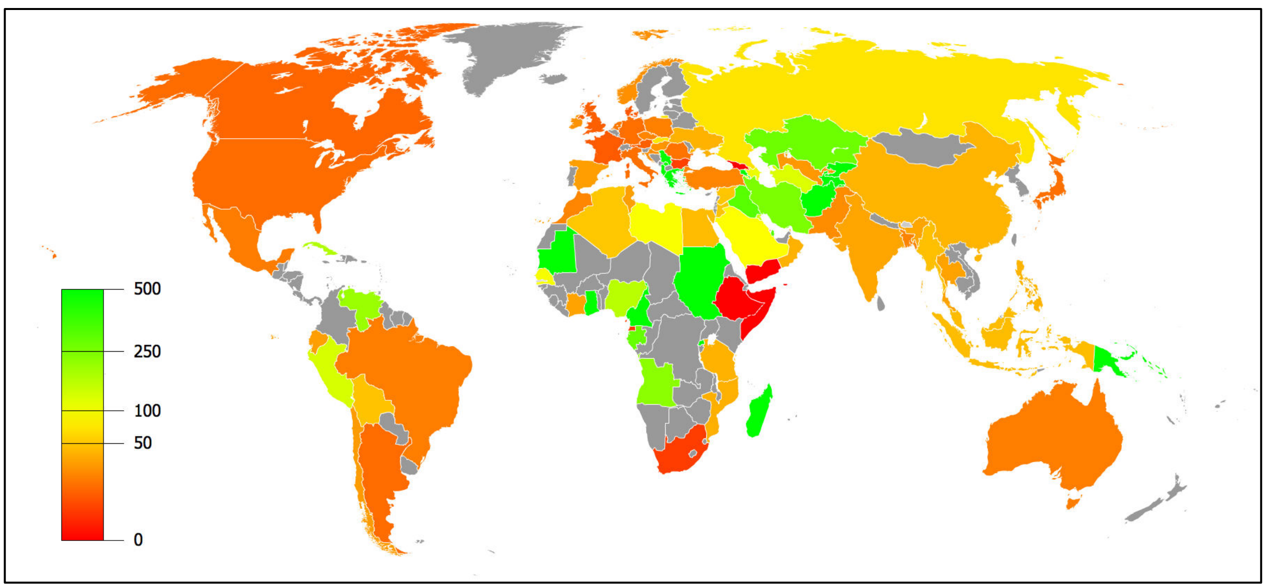

Figure 9-Reserves over production ratios (years) for natural gas across different countries.

2.3 Task 3: Modeling the direct impacts

As explained in task 1, the direct impacts of fossil resource depletion are defined as the additional net present costs that the society has to pay as a consequence of the marginal depletion of a fossil resource.

The marginal price increase due to the depletion of a unit of fossil resource is calculated initially. WEPS+, an energy modeling software is used to model the effects of this increase in price on the global energy market (section 2.3.3). Finally, the total additional costs that the society has to pay as a result of the marginal depletion of the fossil resource are calculated as the costs associated with the changes observed in the global energy market.

2.3.1 Marginal price increase due to a marginal depletion

To calculate the marginal price increase, a curve-fitting model is used (see section 1.3.1.2). Following an approach used in Greene et al (2003), and more recently in Brandt (2011), production costs of fossil resources are modeled using a logistic function curve-fitting model. The price of non-renewable fossil resource, *p*, in dollars per Mega Joule, is modeled as:

$$p = \frac{\ln\left(\frac{1}{\phi} - 1\right) - \alpha_r}{\beta} \qquad \text{Equation 4}$$

Where ϕ is the depletion ratio of the fossil resource, defined as $\phi = \frac{R_{used}}{R_{total}}$ (*MJ/MJ*) . R_{total} (*MJ*) is the total available resources (sum of the resource consumed to date plus remaining available reserves) and R_{used} (*MJ*) is the amount consumed to date. α_r is a dimensionless tuning parameter, and β describes the sensitivity of price to the state of depletion, with units *MJ/$*. A sample logistic figure is presented below.

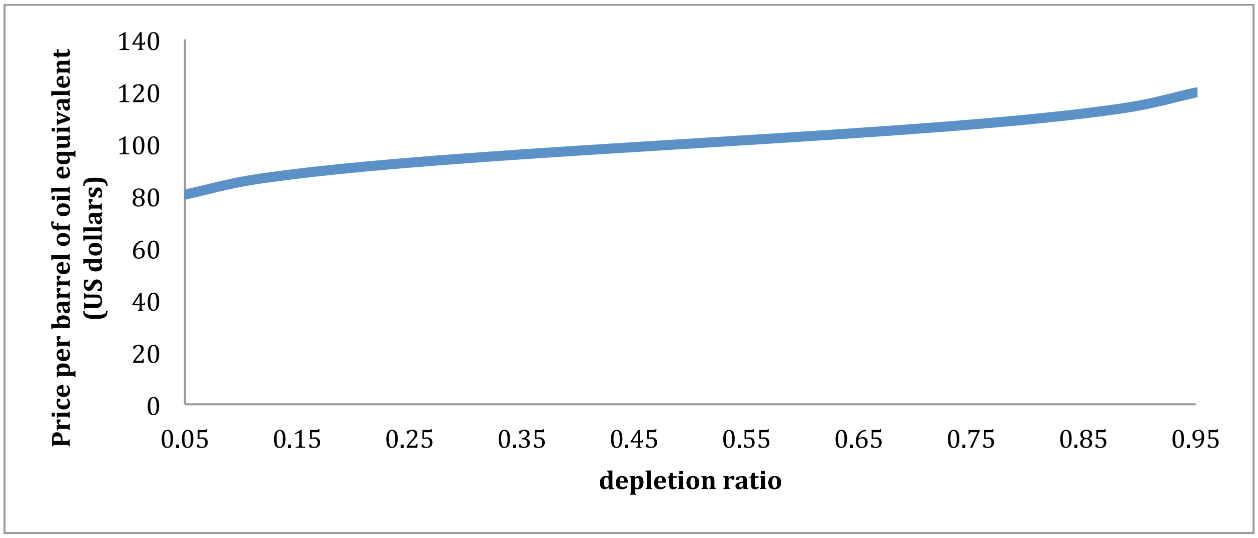

Figure 10 – A sample logistic curve showing an alpha value of 15 and a beta value of -0.15.

The changes in price for a marginal depletion is equal to the slope of the price curve, i.e. the first derivative of the logistic price curve:

$$\frac{dp}{d\phi} = \frac{-1}{\beta\, \phi\, (1-\phi)} \qquad \text{Equation 5}$$

The above equation is used to calculate the slope of the logistic cost curve based as a function of the depletion ratio (ϕ) and β, making it independent of α_r.

In order to relate $d\phi$, a marginal change in the depletion ratio, to *dy (MJ)*, a marginal consumption of the resource, we have:

$$d\phi = \frac{R_{used} + dy}{R_{total}} - \frac{R_{used}}{R_{total}} = \frac{dy}{R_{total}} \qquad \text{Equation 6}$$

where *dy* is the marginal use of a resource.

$$\frac{d\phi}{dy} = \frac{1}{R_{total}} \qquad \text{Equation 7}$$

Since we are interested in the changes in price due to marginal depletion as a consequence of use of *dy*, a marginal use of the resource, we use equations 6 and 7, which gives us:

$$\frac{dp}{dy}=\frac{dp}{d\phi}\times\frac{d\phi}{dy}=\frac{-1}{\beta\,\phi\,(1-\phi)}\times\frac{1}{R_{total}}$$ Equation 8

Where $\frac{dp}{dy}$ is presented in *\$/MJ per MJ dissipated.* The current changes in the price of a fossil resource as a consequence of making a unit amount of the resource unavailable to future users, equal to the marginal price increase, *MPI*, is calculated as follows:

$$MPI_f=\left.\frac{dp}{dy}\right|_{\phi=\breve{\phi}_f}=\frac{-1}{\beta\breve{\phi}_f(1-\breve{\phi}_f)R_{total}}$$ Equation 9

where $\breve{\phi}_f$ is the current depletion ratio of fossil resource *f.*

In calculating the marginal price increase (MPI), the total available reserves and the fraction that is used do not considering non-dissipative uses and anthropogenic stocks.

2.3.2 Choosing the energy forecast model

Various energy forecast models were investigated for the purposes of the study. Only models that considered both the geological and economical aspects of fossil resources depletion (refer to section 2.1.2) were studied. The WEPS+ model (USEIA, 2011) was chosen for the following reasons: WEPS+ is designed and used by the United States Energy Information Administration (USEIA) to produce its annual energy forecasts, which are a credible reference widely used and cited in the industry and academia (USEIA, 2011). Technical support was available through the USEIA office, and the website also provides numerous documentations for the model. WEPS+ modellers were contacted and the exercise was explained. WEPS+ was deemed capable of performing our modeling study. In terms of availability, the WEPS+ model was available for download through the USEIA website.

Energy carriers are categorized in WEPS+ as petroleum, natural gas, coal, nuclear energy, and renewables [consisting of hydroelectric power, geothermal power, solar power (thermal and PV), and wind power]. The world is divided into 16 regions in WEPS+. The economy is divided into five sectors: the residential sector, the industrial sector, the commercial sector, the transportation sector and the electricity sector. The WEPS+ software only makes forecasts up to the year 2035.

2.3.3 Modeling marginal price increases in WEPS+

In this step, the changes in the energy market as a consequence of a marginal price increase of the resource are calculated. Initially, WEPS+ is used to produce a reference scenario where the world production and price of energy by energy-carrier type is forecasted up to the year 2035.

The reference scenario reflects the business-as-usual scenario, and produces the same forecasts that are used in the USEIA International Energy Outlook report (USEIA, 2011).

The consumption matrix, *C*, is defined as a matrix presenting global consumption values by year and energy carrier, where the energy carriers in WEPS+ include: petroleum, coal, natural gas, nuclear, and renewables. The rows of the consumption matrix consist of the energy carriers, *ec,* and the columns consist the years, *y*, between 2012 and 2031. Similarly, the price matrix, *P*, is defined as a matrix reflecting the unit prices with rows consisting of the present worth unit price of the energy carrier and the columns as the years, y, between 2012 and 2031. In WEPS+, all prices are presented in 2009 dollars.

The total costs in the reference scenario that the world has to pay to meet its energy needs between 2012 and 2031 are labelled TC^{ref} and are calculated as:

$$TC^{ref}\ (\$) = \sum_{y=2012}^{2031} \sum_{ec} C_{ec,y} P_{ec,y} \qquad \text{Equation 10}$$

where $C_{ec,y}$ (*MJ*) and $P_{ec,y}$ (*\$/MJ*) are the consumption and price of energy carrier *ec* in year *y*, respectively. *TC* is presented as a value in 2009 dollars. Total costs are calculated for the reference scenario and titled TC^{ref}.

An additional scenario is made, where the unit price of fossil resource *f* is increased by a unit value (for example $1/MJ) for all years between 2012 and 2030. This is done manually in the price input files in the model. The model is run again and the *C* and *P* matrices are obtained. The total costs for the additional scenario for fossil resource *f* are labelled $TC^{add,f}$ and calculated as:

$$TC^{add,f}\ (\$) = \sum_{y=2012}^{2031} \sum_{ec} C_{ec,y}^{add,f} P_{ec,y}^{add,f} \qquad \text{Equation 11}$$

where $C_{ec,y}^{add,f}$ and $P_{ec,y}^{add,f}$ represent the consumption and the prices of energy carrier *ec* in year *y* in the additional scenario for fossil resource *f*, respectively.

The Total Additional Costs as a consequence of a unit increase in the price of fossil resource *f* (TAC_f, expressed in dollars per dollar per mega joule) is the difference between the total costs in the reference scenario and the total costs in the additional scenario for fossil resource *f*:

$$TAC_f\ (\frac{\$}{\$/MJ}) = \frac{TC^{add,f}(\$) - TC^{ref}(\$)}{1\ \$/MJ}$$ Equation 12

The intermediary matrices of price (P) and cost (C) are presented for coal and petroleum in Appendix 3.

2.3.4 Endpoint characterization factors

Characterization factors for fossil resource *f* extracted in country *c* at endpoint are defined as:

$$CF_{f,c}^{endpoint} = FOCSI_{f,c} \cdot MPI_f \cdot TAC_f$$ Equation 13

where $FOCSI_{f,v}$ is the country-specific scarcity indicator expressed in $\frac{MJ\ deprived}{MJ\ dissipated}$;

MPI_f is the global marginal price increase expressed in $\frac{\$/MJ}{MJ\ deprived}$; and

TAC_f is the total additional costs as a consequence of the unit price increase for fossil resource *f*, expressed in $\frac{\$}{\$/MJ}$.

The characterization factor has a unit of $/MJ dissipated. The MPI, as calculated in section 2.3.1, refers to the global additional costs as a consequence of making the resource less available to users. The same logic behind FOCSI at midpoint is applied to the endpoint characterization factor: if a resource is abundant for users in a region (FOCSI= 0) every MJ dissipated doesn't lead to less availability for future users. The midpoint indicator FOCSI is therefore used to discriminate between price increases in countries with different scarcity levels. According to this logic, it is considered that the product of FOCSI and MPI is the price increase to users in accordance to the level of scarcity of the resource in a given region.

It should be noted that in calculating the *MPI,* since a unit increase in price (1 \$/MJ) is used in the additional scenario, and then interpolated to represent an *MPI* increase in price, we are using linear interpolation. In order to confirm that this is a correct assumption, the relationship between the increase in unit price and total costs is studied. The results confirmed that linear interpolation is appropriate. Appendix 6 presents the methodology for carrying out this evaluation.

2.3.5 Calculating the endpoint characterization factors

In calculating the MPI, a value of -0.15 for β was used in our modeling. This value is based on the literature. Using historical data on prices and states of depletion, Greene et al. (2003) inferred a global value of beta of -0.15 for oil and gas reserves using global data . Brandt (2011) has later used this value for oil, coal and natural gas. The total used reserves (R_{used}) are adapted from Brandt et al, (2010), which is used in their modeling. Total available resources (R_{total}) are calculated as the sum of cumulative production to date and 2P reserves estimates (Greene et al, 2003, Brandt, 2011). R_{used} and R_{total} values are presented in table 10.

Table 10- Total available resources R_{total}, resources consumed to date R_{used}, and marginal price increase (MPI)

	R_{total} (J)	R_{used} (J)	MPI $(\frac{\$/MJ}{MJ\ deprived})$
Coal	$5.09{\times}10^{21}$	$3.75{\times}10^{22}$	$1.69{\times}10^{-21}$
Natural Gas	$1.187{\times}10^{21}$	$7.40{\times}10^{21}$	$2.89{\times}10^{-21}$
Petroleum	$3.98{\times}10^{22}$	$5.65{\times}10^{21}$	$5.20{\times}10^{-20}$

The consumption matrix *(C*) and price matrix (*P*) for the baseline scenario are presented in Tables 1 and 2 in Appendix 3. The WEPS+ model does not provide prices for nuclear and renewable energies, so these prices were extracted from the Energy Technologies Perspective report issued by the International Energy Agency (IEA, 2012b). A discount rate of 3 percent is used when calculating the prices over the next 20 years, similar to ReCiPe (Goedkoop et al., 2009).

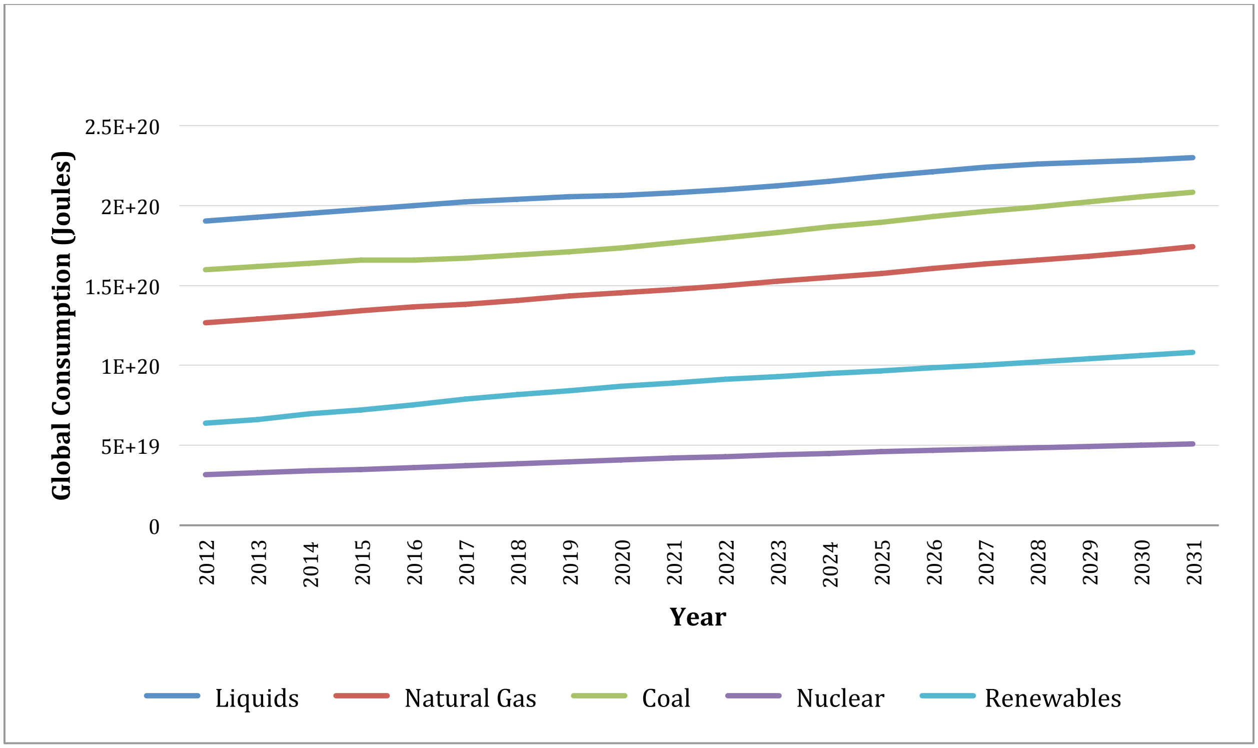

Figure 11- WEPS+ Global consumption results (2012-2031) for the reference scenario

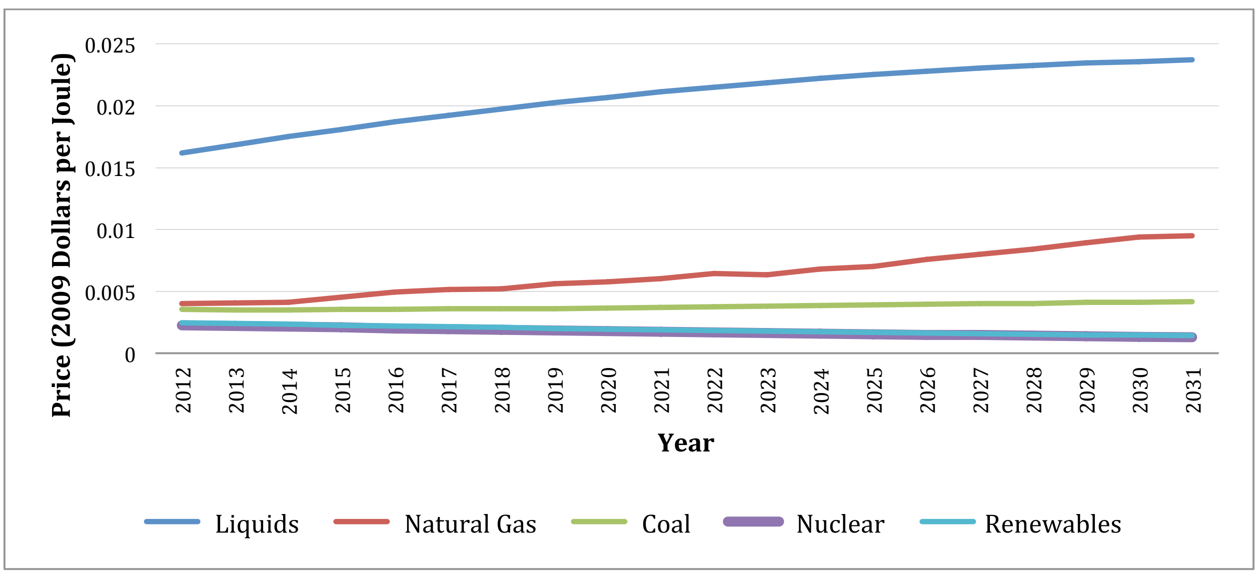

Figure 12- Prices by energy carrier type (2009 dollars per joule) for the reference scenario

In the next step, TAC values were calculated. Instead of using a 1-dollar unit price increase when calculating the additional scenarios, a 1-cent per billion BTU price increase is applied to the reference scenario in WEPS+ (this is done to be consistent with the units that WEPS+ uses). Modeling for natural gas was not successfully carried out at this stage as there was a glitch in the model for natural gas. TAC matrices were only calculated for petroleum and coal. They are presented in tables 4 and 5 in Appendix 3.

FOCSI values from task 2 were used in calculating the endpoint characterization factors. The characterization factors are presented in the results and discussion chapter.

2.4 Task 4: Modeling the indirect impacts

As explained in Task 1, the indirect impacts associated with the depletion of fossil resources are defined as the life cycle impacts of the adaptation of the energy market to the marginal increase in the price of a fossil resource due to depletion.

WEPS+ output data is used for assessing the adaptation of the market. WEPS+ allows the classification of the total additional global energy use into five economical sectors that consume energy (residential, commercial, industrial, transportation, electricity).

The sector-specific total additional consumption for fossil resource *f*, titled $TACON_f^*$, is defined as a matrix that represents the additional consumption of different energy carriers as a consequence of a unit increase in the price of fossil resource *f*, with rows consisting of the energy carrier used in various sectors, *s,ec* and the column representing the additional consumption between 2012 and 2031. The $TACON_f^*$ matrix is calculated using the total sector-specific consumption matrices C^{ref} and $C^{add,f}$ for the reference scenario and the additional scenario for fossil resource *f*:

$$TACON_f^* = C^{add,f} - C^{ref}$$

The numbers on each row of the matrix are summed up into one number representing the total additional consumption of an energy carrier in a sector between 2012 and 2031. The simplified matrix, which only has one column (representing total additional consumption between 2012 and 2031) is titled $TACON_f$.

$$TACON_f = \sum_{j=2012}^{2031} TACON_{f\,i,j}^* \qquad \text{Equation 14}$$

The $TACON^*$ matrices for coal and petroleum are presented in tables 1 and 2 in Appendix 4 and in Figures 18 and 20 in Chapter 3.

The TACON* matrices for petroleum and coal were modeled in Simapro. The indirect impact for the dissipation is defined as the cross product of the amount of resource dissipated, FOCSI, MPI, and the sum of the life cycle impacts from the TACON matrix :

$$Indirect\ Impacts = Resource\ dissipated\ (MJ)\times\left[\sum\ Supply\ share_i\ (\%)\times FOCSI_i\left(\frac{MJ\ deprived}{MJ\ dissipated}\right)\right]\times MPI\left(\frac{\$/MJ}{MJ\ deprived}\right)\times\sum Impact(TACON_i) \quad \text{Equation 15}$$

The generic processes produced in the next section are used in Simapro to model the impacts associated with the TACON matrix. ReCiPe (Goedkoop et al, 2009) was used for calculating the environmental impacts in the human health and ecosystem health impacts categories. The results are presented in the results and discussion chapter.

2.4.1 Modeling in SimaPro

SimaPro is a commercially available software that allows the calculation of the life cycle impacts of products and services. It is used to calculate the life cycle environmental impacts of the *TACON* matrix. The Ecoinvent database version 2.2, available in SimaPro, is used to model the sector-specific energy consumption processes.

In identifying the marginal affected user, it is assumed that the modes of transport are affected proportional to their share of the transportation market. Alternatively, Ekvall & Weidema (2004) has proposed guidelines for identifying one marginal affected user. However, since information regarding which user will be the marginal affected user in each sector is not available, the former assumption is made.

Below, we explain how the Ecoinvent database was used to model the generic processes that represent the consumption of energy for different energy carriers in different sectors.

2.4.1.1 Transportation:

The US Department of Transportation (2012) provides data on energy use by mode of transport in the United States. This data is used as a proxy for the global distribution of how each fossil resource is used in the transportation sector. The Ecoinvent processes used to model transportation and comments are presented in Tables 28 and 29 in Appendix 1.

In WEPS+, biofuels consumption is presented under the liquid fuels category along with petroleum. No distinction is made between petroleum and biofuels and they are both presented as one bulk number. Biodiesel and ethanol are the two fuels that are produced noticeably at a global level (US Department of Energy, 2012). Ethanol and biodiesel are both used almost entirely in the transportation sector, therefore we model their use in Simapro under the transportation sector. In 2011, the world production of ethanol and biodiesel added up to 86.1 and 21.4 billion liters respectively. Using an HHV of 33.8 MJ/lit for biodiesel and 23.44 MJ/lit for ethanol (Alternative fuels data center, n.d.), and a total consumption value of 0.1 quadrillion MJs from WEPS+ results for 2011 in the transportation sector, we calculate that biofuels account for 3.3 percent of the share of the production of transportation liquid fuels in 2011. We use this percentage in defining the share of biofuels in the global mix of transportation liquid fuels.

2.4.1.2 Residential, commercial and industrial sectors

In the residential and commercial sector, we used statistics for the United States (D & R. International, 2012) on the functionalities that energy carriers provide. Natural gas, petroleum and renewables are used almost entirely for heating purposes (96%, 97%, and 98% respectively), and the remaining is used for cooking, which can also be modeled as a heating process. In the commercial sector in the United States, statistics (D&R International, 2012) show that natural gas, petroleum and renewables are also used almost exclusively for heating (92%, 96%, and 93%). No information is found on coal use in a residential or commercial setting, so we assume that similar to other energy carriers, it is used for heating purposes. To find the appropriate ecoinvent process that represents heating using petroleum, all the available processes for heat produced by light fuel usage were compared. Light fuel oil, burned in boiler 10kW condensing, non-modulating/CH S was deemed to be the most representative of all heating uses in a residential setting. To find the appropriate process in ecoinvent that represents heating, the processes available for heating using natural gas in the residential sector, the available processes were compared in simaPro using the Impact 2002+ life cycle impact assessment method. It was observed that all processes have relatively similar impacts, therefore once again the median process was chosen (Natural Gas, burned in boiler modulating <100 kW/RER S). For coal heating applications, out of the four available processes, the median process was used (Hard Coal, burned in industrial furnace 1-10 MW/RER U). Renewables use in the residential sector is all assumed to be for heating purposes. This is modeled as burning logs in a furnace (Logs, hardwood, burned in furnace 30 kW).

Since no statistics was found in the literature that would identify energy carriers use in the industrial sector by end-use applications, we assume that all energy used in the sector is in heat production. For the industrial sector, we used the same processes in Ecoinvent as used for the residential commercial sector, except petroleum heating, which is modelled using "Heavy fuel oil, burned in refinery furnace/MJ/RER S".

2.4.1.3 Electricity

Electricity by coal: Ecoinvent has processes for electricity production for various countries and regions. The processes are however not available for all countries. In order to create a global coal electricity production process, the share of each county's coal consumption in overall global consumption of coal is used. In creating the global electricity production, the share of each process was increased proportionally so that the sum of the available processes add up to 100% (see Table 30 in Appendix 5).

Electricity by natural gas: A similar approach to the above was carried out for electricity by natural gas (see table 31 in Appendix 5).

Electricity by petroleum: Ecoinvent has processes for electricity production only for the European Region, which is the process we used (Heavy Fuel Oil, burned in power plant/RER).

Electricity by renewables: No global data was found for the shares of different types of renewables in overall renewable energy production. The United States breakdown of renewable energy (US Department of Energy, 2012), presented in Table 12 (below), was therefore used as a proxy for the world. Geothermal energy, which accounts for three percent of the share of renewable energy in the United States, is not available in the Ecoinvent database and therefore was not used in creating a generic renewable-electricity process. The processes used for hydro and solar, the share of each country's consumption in overall consumption was used (see Tables 31 and 32, Appendix 5). For biomass and wind, the only available options in Ecoinvent were selected.

Table 11- Renewable energy production in the United States (source: US Department of Energy, 2012)

Renewable Energy type	Percentage	Ecoinvent generic process
Hydro	35.96%	see table 31, Appendix 5
Solar	0.88%	see table 32, Appendix 5
Biomass	50.00%	Electricity, wood at distillery
Wind	13.16%	Electricity, at wind power plant/RER

2.5 Task 5: Results evaluation

To evaluate the obtained results, two tasks were performed:

2.5.1 Comparison of obtained characterization factors

In this task, the obtained characterization factors were compared with characterization factors from selected existing LCIA methods. The goal of this task is to identify the added value of our characterization factors to existing LCIA methods.

2.5.2 Sensitivity Analysis

In order to identify the extent to which the uncertainty in parameters used in the calculations affect the midpoint and endpoint characterization factors and to test the different assumptions made throughout the course of calculations, a systematic sensitivity analysis is performed on a series of selected parameters. The numerical values used for these parameters are either data that have been retrieved from databases (such as reserves or production data), or assumptions that have been made in the methodological framework (such as upper and lower time horizons for calculating FOCSI values). In either case, these numbers can be subject to changes, and it is the goal of this task to identify the sensitivity of the characterization factors to a change in these parameters.

In performing the sensitivity analysis, the numerical values used in the calculations for a selected parameter were subsequently increased and decreased by 25 percent, and the effect on the calculated characterization factors was recorded. The results are presented as a percentage of change in characterization factor values.

2.5.2.1 Sensitivity of midpoint characterization factors

The parameters studied at midpoint level are as follows:

Lower Limit (LL): This parameter represents the R/P (years) value which has been chosen to represent the countries with maximum scarcity. This parameter is selected based on the logic explained in section 2.2. Overall, as this parameter is chosen arbitrarily, there is no indication of uncertainty.

Upper Limit (UL): This parameter represents the R/P value after which a resource is considered abundant. As this parameter is chosen arbitrarily, there is no indication of uncertainty.

Reserves values: As explained in section 2.2.2, reserves estimates are subject to uncertainty. Economic reserve estimates are divided into three categories: proven, possible and probable. For the purposes of this research, 2P reserve estimates were used in the calculations.

Annual production: Annual production rates were studied from 1991 to 2012 (BP, 2012). For all three fossil resources, with the exception of minor fluctuations, an increasing trend was observed in annual productions. As we are interested in the current reserves to production rates, the most recent annual extraction rates were used.

2.5.2.2 Sensitivity of endpoint characterization factors

Endpoint characterization factors are comprised of three components, namely FOCSI, MPI and TAC. Each of these components are calculated using assumptions and/or using data with uncertainty. The sensitivity of FOCSI to selected parameters was explored in Task 4. The parameters selected for the sensitivity analysis of MPI and TAC values are β, R_{used}, R_{total} (used to calculate MPI), and the number of years values (used to calculate TAC).

2.5.2.3 Scenario studies

Scenario #1 was explored where the two time horizons used to calculate FOCSI values are replaced with the short term and medium term time horizons of 20 and 100 years. The effect of this scenario on midpoint and endpoint characterization factors is explored.

Scenario #2 explores the impact of replacing 2P reserves with 3P reserves in the reserves-over-production calculations on midpoint and endpoint characterization factors.

2.6 Task 6: Illustrative examples

In this task, case studies are performed to demonstrate how the impacts associated with the use of 1 MJ of petroleum, coal or natural gas by a user in a certain country can be calculated using the obtained characterization factors, supply mixes for a country.

The objective of the illustrative example is to evaluate the model by presenting a concrete example of how the proposed characterization factors can be used to calculate direct impacts at midpoint and endpoint as well as indirect impacts. The results are interpreted and compared with those from EDIP and CML at midpoint and with ReCiPe at endpoint. Through these examples, the contribution of the intermediary parameters in the model is discussed, and the added value of the new model is explored.

High coal, natural gas, or petroleum-consuming and importing countries (BP, 2012) were selected for this exercise. The supply mix for each country is derived based on import, export, and production data. The selected countries along with their supplying countries and supply shares are presented in Tables 12 and 13 for coal and natural gas respectively. For petroleum, no specific country is chosen since the characterization factors apply to all countries.

Table 12 – Selected countries and supply mixes for coal example

Selected country	Supply mix of coal	
	Source Country	Supply share
China	China	95.6%
	Indonesia	1.45%
	Australia	1.67%
	South Africa	0.54%
	Russia	0.31%
India	India	88.3%
	Indonesia	3.9%

	South Africa	3.9%
	Australia	3.9%
United States	United States	98.0%
	Canada	2.0%
Japan	Japan	1.0%
	Australia	99.0%
Russia	Russia	87.5%
	Kazakhstan	12.5%

Table 13 – Selected countries and supply mixes for natural gas example

Selected country	Supply mix of Natural Gas	
	Source Country	Supply share
United States	United States	83.9%
	Canada	15.9%
	Mexico	0.2%
Russia	Russia	98.07%
	Azerbaijan	0.04%
	Kazakhstan	0.71%
	Turkmenistan	0.57%
	Uzbekistan	0.61%
United Arab Emirates	UAE	71.33%
	Qatar	28.76%

Iran	Iran Azerbaijan Turkmenistan	95.76% 0.22% 4.03%
Qatar	Qatar	100%

CHAPTER 3 RESULTS AND DISCUSSION

3.1 Midpoint characterization factors

3.1.1 Petroleum

With a global reserves-over-production value of 62.7 years, all users have the same FOCSI value of 1.0 MJ deprived/MJ extracted.

3.1.2 Coal

FOCSI values for coal are presented in a visual format in Figure 13 below. It can be observed that FOCSI values for coal vary considerably across the globe (between 0 and 1.0 MJ deprived/MJ dissipated). This leads to an increased discriminating power when assessing coal consumption in different countries both at midpoint and endpoint level.

In LCA the information about the location of an environmental intervention is not always available. A weighted global factor is calculated for these situations, where the weighted average of all FOCSIs using the country's annual production is used as the weighting factor. This takes into account the probability of extracting a given fossil resource from a given country. The resulting global FOCSI is equal to 0.82 MJ deprived/MJ extracted.

FOCSI values for coal are presented by country in Table 2 in Appendix 1.

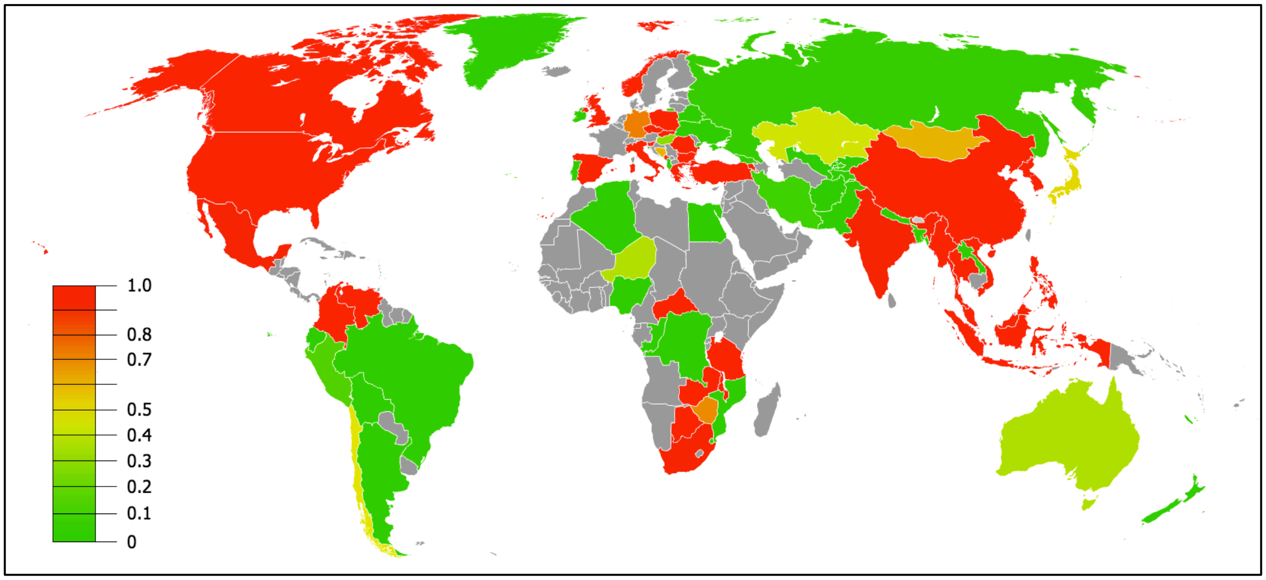

Figure 13 - Coal FOCSI values (MJ deprived/MJ used dissipatively) for different countries. Grey is used for countries that have no reserves.

To further analyze the variation in FOCSI values, Figure 14 (below) is presented, where for each country, the height of the block is equal to the FOCSI associated with the country, and the width is equal to the annual production in that country. The resulting areas represent the magnitude of a country's annual production, weighted according to the scarcity of its resources. Countries are ranked according to annual production. From the graph, it can be seen that there exists quite a variety in the level of scarcity. For example, China, the number one producer of coal has a FOCSI value of 1.0 MJ/MJ, while Australia and Russia, the fourth and fifth largest producers of coal, have FOCSI values of 0.37 MJ/MJ and 0.05 MJ/MJ respectively. The red line presents the global average FOCSI of 0.82 MJ/MJ.

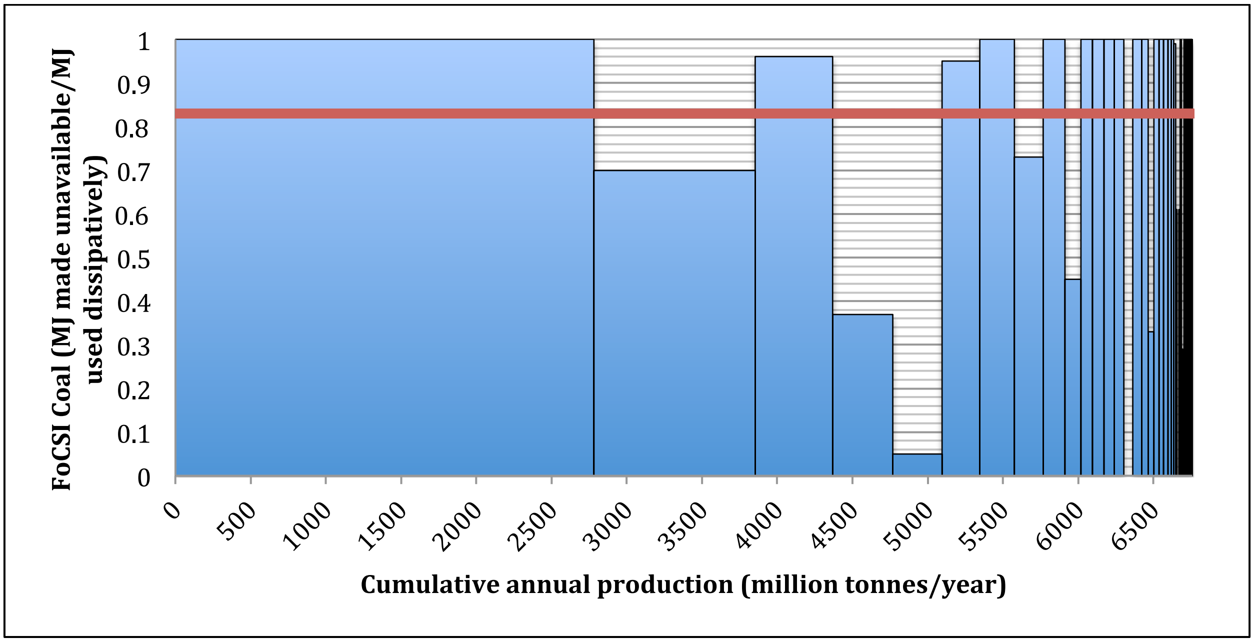

Figure 14 - Area graph for coal with cumulative annual production (million tonnes /yr) on the x - axis and FOCSI values on the y-axis.

3.1.3 Natural Gas

Figure 15 is a graphical presentation of FOCSI values for countries across the world. As it can be seen, compared to coal, more countries in this graph are represented in red, indicating FOCSI values of 1.0 MJ/MJ. Natural gas is generally scarcer than coal. It is observed that in countries that have natural gas resources, FOCSI values vary. This results in regional discriminating power in impact characterization at midpoint and endpoint.

An area graph was plotted for natural gas FOCSI values (Figure 16) as was done for coal. In the top ten producing countries, Iran and Qatar have FOCSI values of 0.61 and 0.43 MJ/MJ respectively, while other countries have FOCSI values of 1.0 MJ/MJ. When there is no information available regarding the source of natural gas that is being used in an LCA study, the global FOCSI value should be used. Similar to coal, the weighted average of all FOCSIs using the country's annual production as the weighting factor is calculated. The resulting global FOCSI for natural gas is equal to 0.96 MJ deprived/MJ extracted.

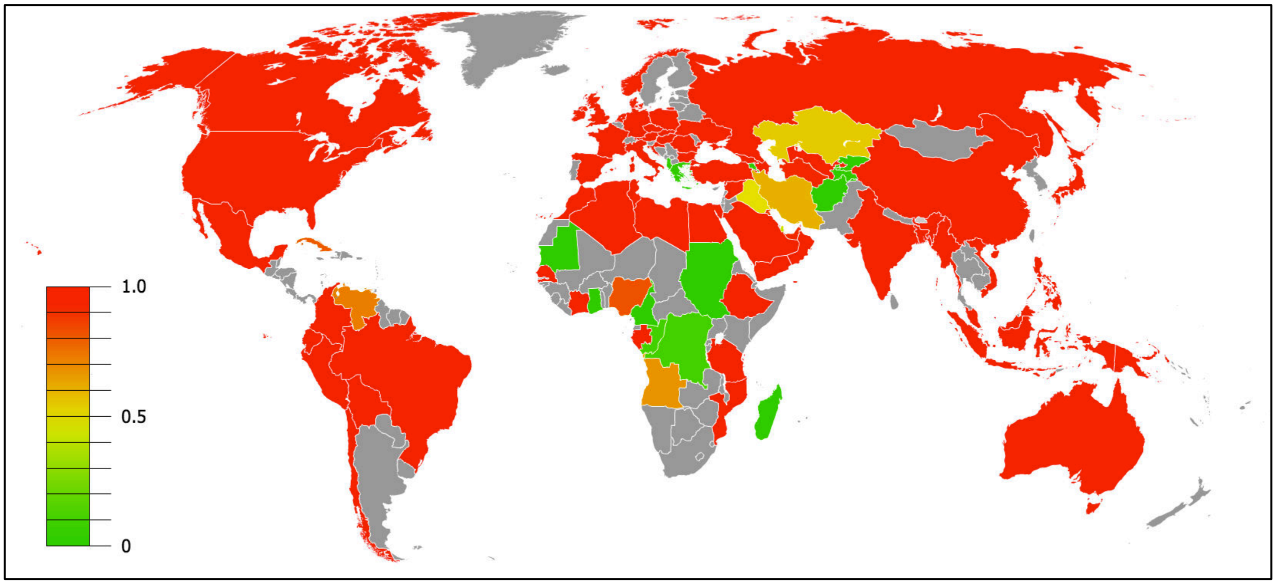

Figure 15-Natural Gas FOCSIs. Grey is used for countries that have no reserves.

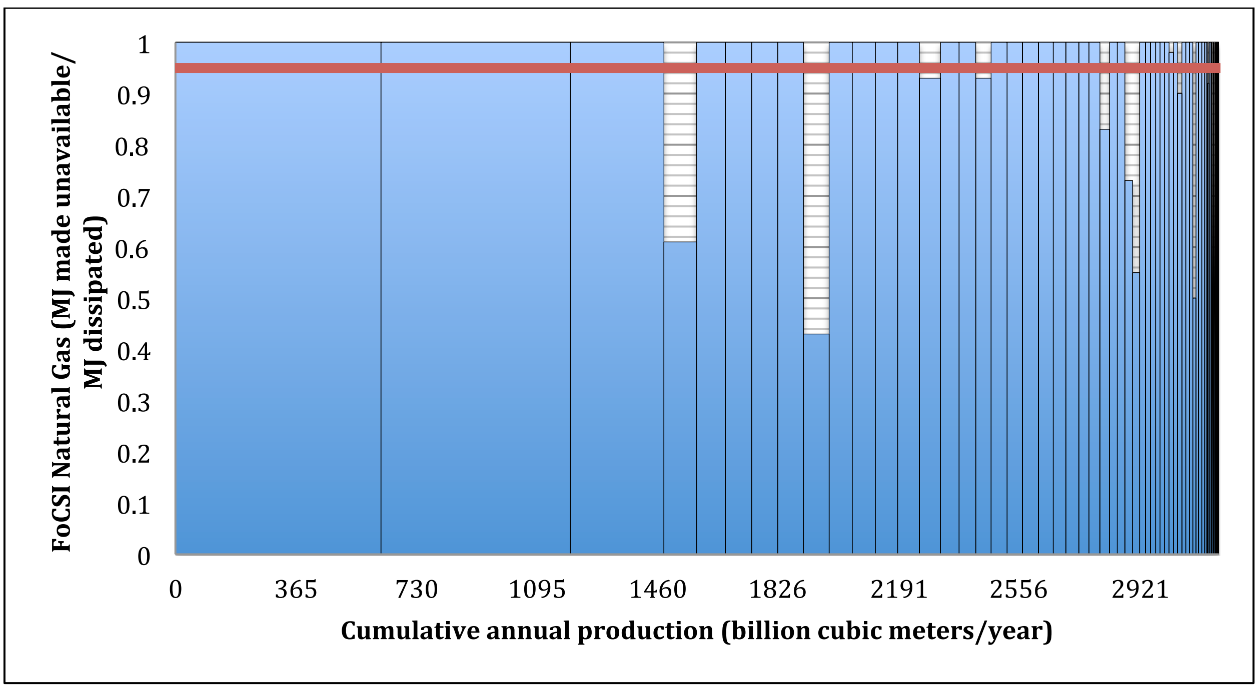

Figure 16 - Area graph for natural gas with cumulative annual production (billion cubic meters /yr) on the x -axis and FOCSI values on the y-axis.

3.2 Endpoint Characterization factors

TAC values for petroleum and coal are presented in the Table 13. These values show the total additional costs that society has to pay as a consequence of a 1 \$/MJ increase in the price of the fossil resource. An increase of 1 \$/MJ in the unit of petroleum or coal is unrealistic (the 2010 prices for coal and petroleum were 0.0022 \$/MJ and 0.0133 \$/MJ, respectively), but presented as is to comply with the units used in Equation 2 to calculate the direct impacts.

Table 14 - Total Additional Costs (TAC) values for petroleum and coal

	TAC (\$ per \$/MJ)
Petroleum	9.59 E+16
Coal	3.32 E+17

Using region-specific FOCSI values, and fossil resource-specific MPI and TAC values, the endpoint characterization factors are calculated for coal and petroleum. For petroleum, a FOCSI value of 1.0 leads to one global endpoint characterization factor, presented in Table 15. The global characterization factor for coal, using the global FOCSI value of 0.82, is presented in Table 15. For coal and petroleum, the country-specific endpoint characterization factors are presented in tables 1 and 2 in Appendix 2.

Table 15 - Endpoint characterization factors for petroleum and coal (global weighted average)

	Characterization factor (\$/MJ dissipated)
Petroleum	4.90×10^{-3}
Coal (global weighted average)	4.56×10^{-4}

The following observations were made regarding WEPS+ results:

1) As a consequence of an increase in the price of coal (due to the depletion of 1 MJ), the WEPS+ model predicts that coal use will be partially replaced by natural gas. This is shown in Figure 17, where cumulative coal consumption is reduced by 5.71 MJ and natural gas consumption is increased by 3.84 MJ following the depletion of 1 MJ of coal.

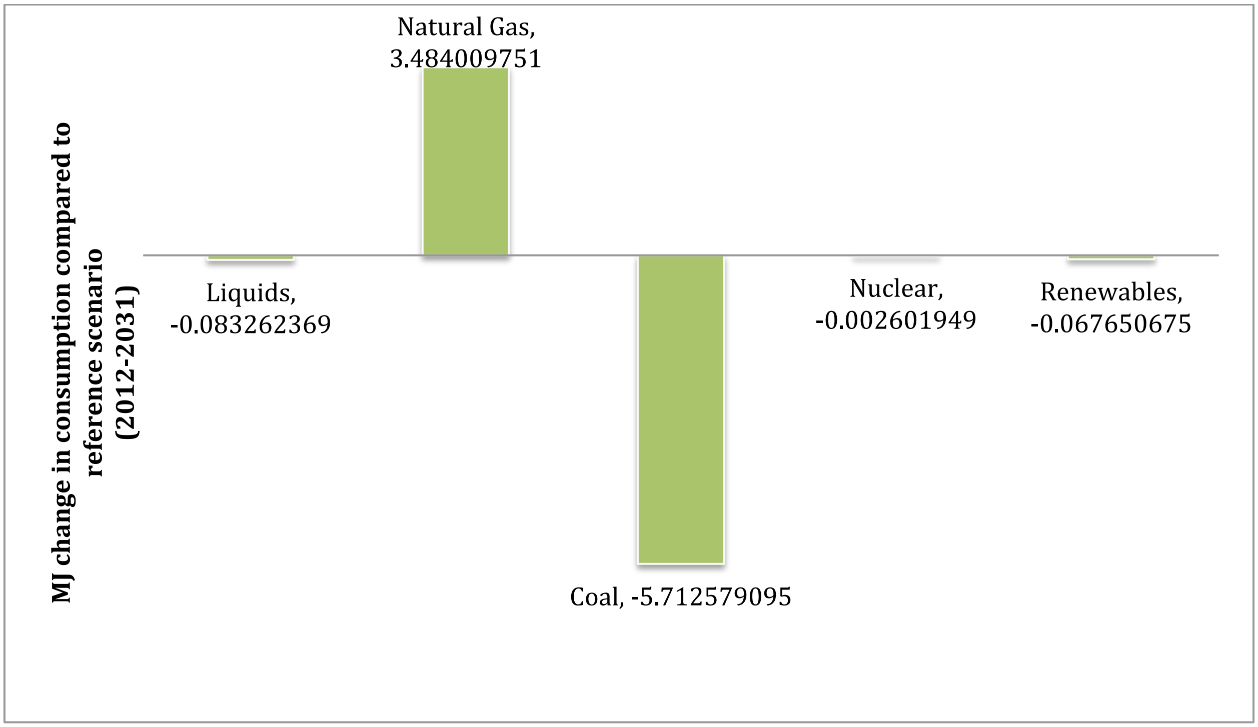

Figure 17-Changes in global production (*MJ*) of coal as a consequence of 1 MJ of coal deprived

Figure 18 (below) further shows that these changes take place almost entirely in the electricity sector. This is due to the fact that the electrical sector is more flexible to change from coal to natural gas compared to other sectors.

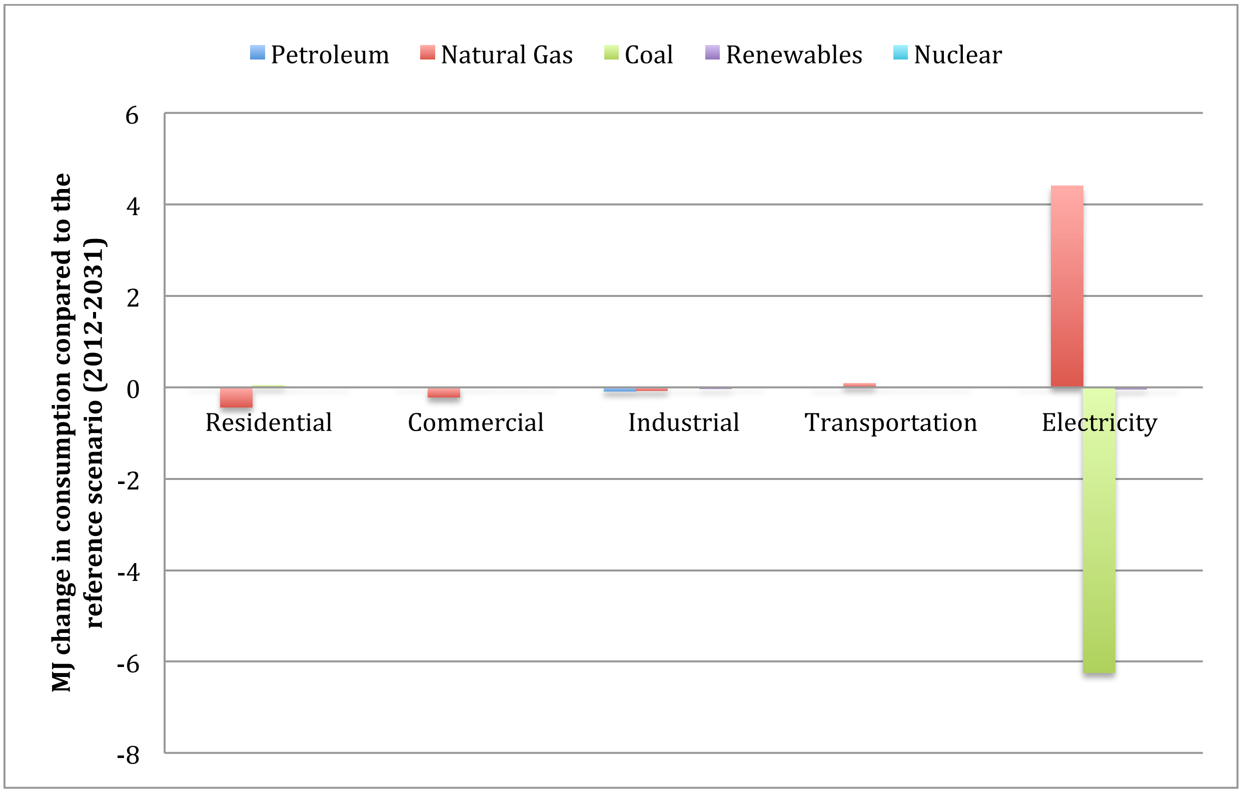

Figure 18- Changes in world production (MJ) (2012-2032) as a consequence of 1 MJ of coal deprived

2) As figure 19 (below) shows, an increase in the price of petroleum causes a decrease in the consumption of all energy carriers. This is an indication of the economy's dependence on petroleum. Higher oil prices have a negative effect on a country's GDP, affecting the overall consumption of energy in all sectors. This elastic relationship between oil prices and a country's GDP is used in WEPS+ modeling (USEIA, 2011c). In the following figure (Figure 20), changes in global consumption between the new scenario and the reference scenario are presented by sector. It is observed that in the residential and commercial sectors, a slight increase in natural gas is predicted, possibly due to the switch from heating oil to natural gas. In the industrial sector, the consumption of all energy carriers is decreased, an indication of the effect of petroleum prices on economic activity (the higher the price, the lower the GDP). Comparison with reference scenario results showed that the transportation sector is also affected; each fuel is affected proportionally to the total consumption between 2012 and 2031 in the reference scenario. The electric power sector is affected proportionally to reference scenario consumption patterns as well, except for renewables

and nuclear, which are affected less. Nuclear power prices are unrelated to petroleum prices and renewables boom as a consequence of high oil prices (Toth & Rogner, 2006) resulting in a smaller overall effect in their production.

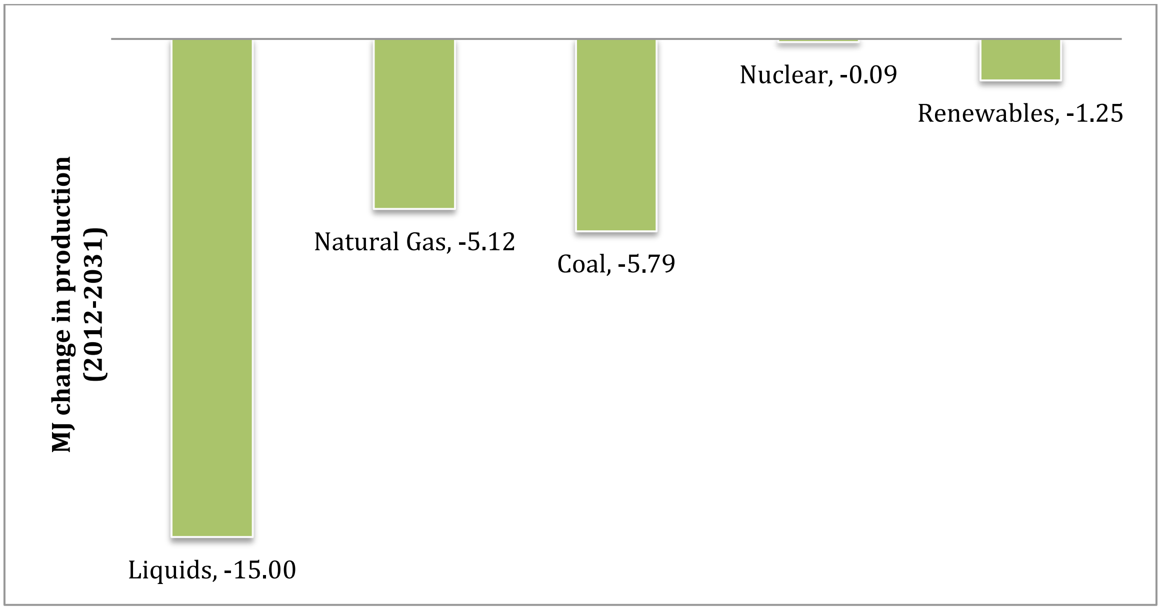

Figure 19- Changes in world production (2012-2013) (in MJ) in comparison to the reference scenario as a consequence of 1 MJ of petroleum deprived

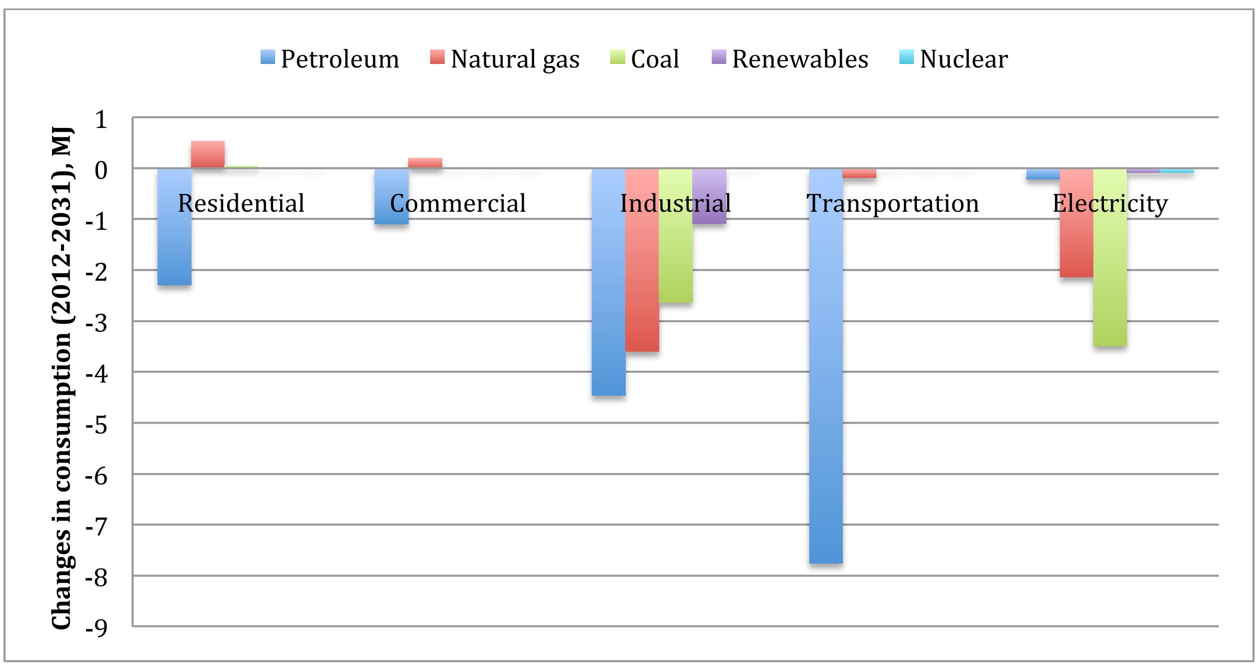

Figure 20- Changes in world production (2012-2032) as a consequence of 1 MJ of petroleum deprived

3.3 Indirect impacts

The global weighted indirect impacts of 1 MJ deprived for a country with FOCSI values are presented in Table 16 (below). As it can be seen from figures 21 and 22 (below), for both petroleum and coal, the indirect impacts of the depletion in both impact categories of human health and ecosystem health have negative values. A negative impact value is considered an “avoided impact”.

Table 16 - Indirect impacts of the depletion of 1 MJ of petroleum and coal

	Human Health (DALYs)	Ecosystem Health (species.yr)
Petroleum	-5.39×10^{-6}	-2.47×10^{-8}
Coal	-1.41×10^{-6}	-5.57×10^{-9}

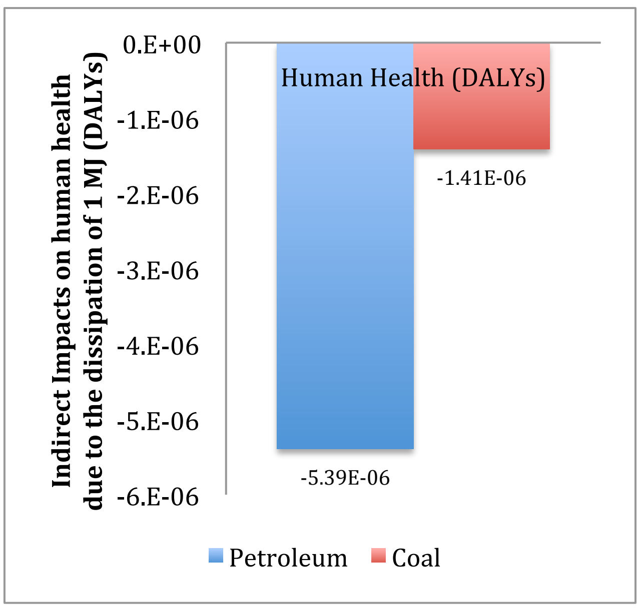

Figure 21 – Indirect impacts on human health

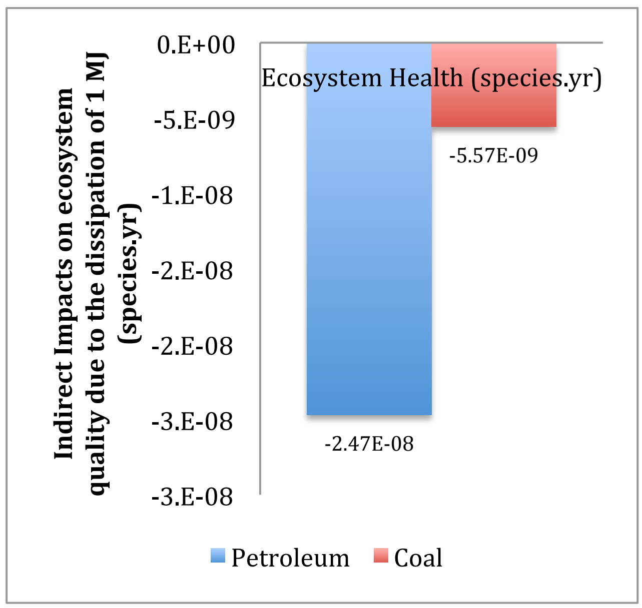

Figure 22 – Indirect impacts on ecosystem quality

3.3.1 Petroleum

As previously explored in Figure 14 of section 3.2, the depletion of 1 MJ of petroleum leads to reductions in the consumption of all energy carriers. This leads to greater avoided impacts for petroleum compared to coal. The indirect impacts due to the depletion of 1 MJ of petroleum are segregated according to energy carriers and presented in Table 17.

Table 17 - Indirect impacts from the depletion of 1 MJ of petroleum segregated by impacts from each energy carrier

	Petroleum	Natural Gas	Coal	Nuclear	Renewables
Human Health (DALYs)	-3.07E-06	-5.49E-07	-1.72E-06	-6.99E-10	-5.67E-08
Ecosystem Services (species.yr)	-1.35E-08	-2.98E-09	-7.06E-09	-2.43E-12	-1.09E-09

As it can be seen in Figure 23 and 24 below, the greatest indirect impacts in both impact categories (more than 50% of total indirect impacts) result from the reduction in the overall global consumption of petroleum. Referring to Figure 14, it can be seen that this is expected, as the largest reduction in production is observed in petroleum (15 MJ). However, although natural gas and coal have relatively similar reductions in production (5.12 MJ and 5.79 MJ, respectively), the resulting avoided impacts from coal are more than double those from natural gas in both impact categories (32% for coal versus 10% for natural gas in the human health category, and 29% for coal versus 12% for natural gas in the ecosystem health category). This is attributed to the smaller environmental impacts from natural gas compared to coal. Renewables account for less than 5% of the impacts in both categories, followed by nuclear, which accounts for less than 1 percent of the total impacts.

Figure 25 (below) presents the contribution of different energy carriers to the direct impacts (calculated using the proposed methodology) and the indirect impacts for coal. The direct impacts do not follow the same trends as the indirect impacts. The greatest portion of the direct impact, and the only positive one, is from petroleum. This is due to the fact that even though the amount of petroleum consumed is reduced, the increase in price has lead to overall positive additional costs. The negative impacts from other energy carriers are less significant compared to those from petroleum, and are ranked from largest to smallest as natural gas (-3.0%), coal (-0.5%), renewables, and nuclear (< -0.5%).

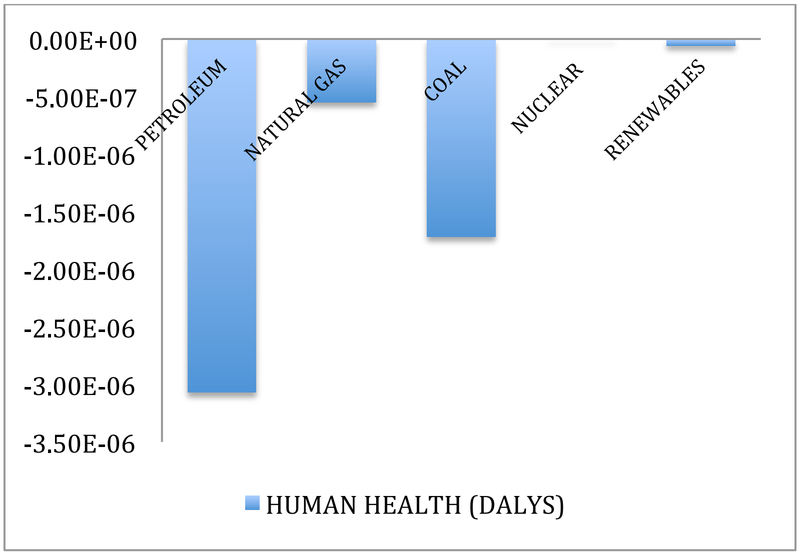

Figure 23 - Indirect impacts on human health in DALYS per MJ of petroleum dissipated

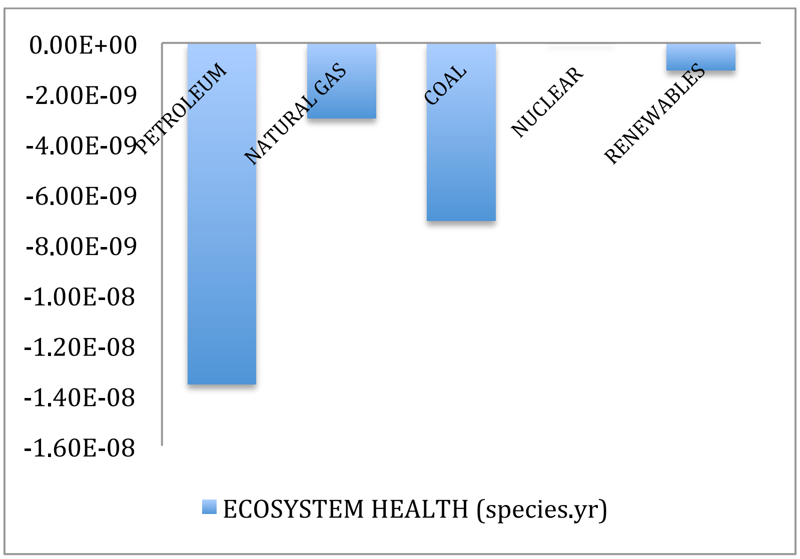

Figure 24 - Indirect impacts on ecosystem health in species.yrs per MJ of petroleum dissipated

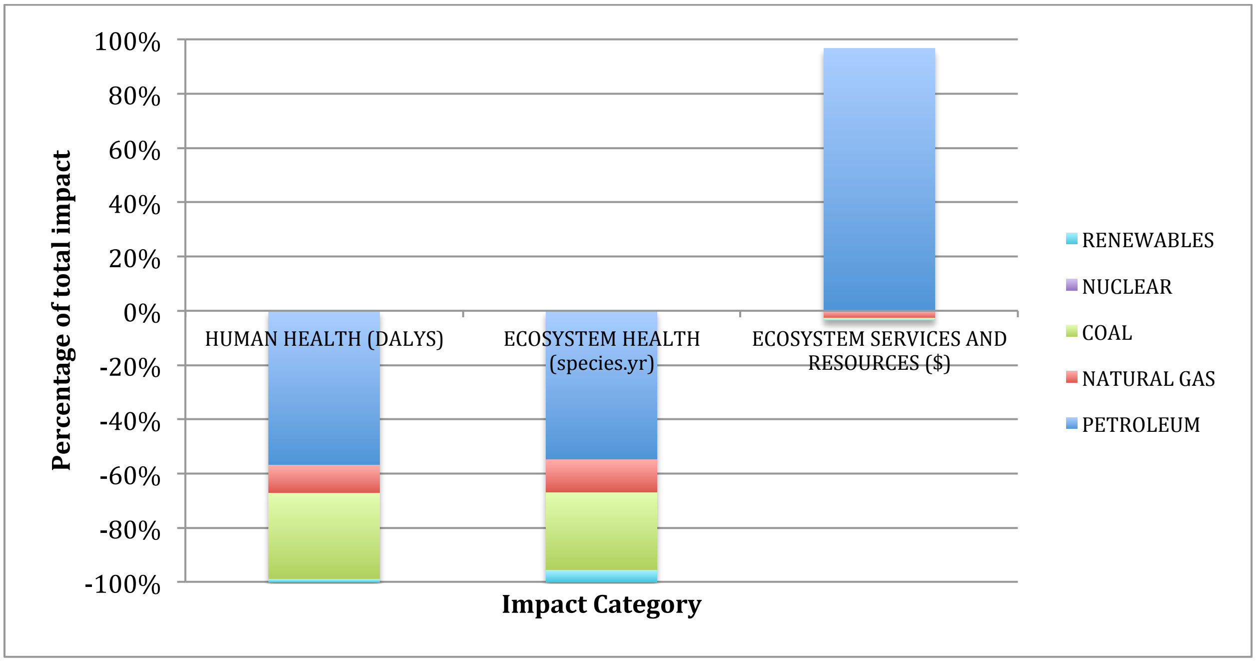

Figure 25 - Contribution of different fossil resources in the indirect impacts (on Human health and ecosystem quality) and direct impacts of fossil resource depletion for 1MJ of petroleum

3.3.2 Coal

The indirect impacts due to the depletion of 1 MJ of coal are segregated according to energy carriers and presented in table 18.

Table 18 - Indirect impacts from the depletion of 1 MJ of coal segregated by impacts from each energy carrier

	Petroleum	Natural Gas	Coal	Nuclear	Renewables
Human Health (DALYs)	-2.39E-08	6.65E-07	-2.05E-06	-2.29E-11	-2.64E-09
Ecosystem Services (species.yr)	-9.12E-11	3.01E-09	-8.44E-09	-7.96E-14	-6.12E-11

In Figure 12, it was observed that as a consequence of the depletion of 1 MJ of coal, natural gas and coal consumption are most affected. This also holds true for the indirect impacts, where the dominating impacts are due to natural gas and coal. The increase in the use of natural gas leads to additional positive impacts, whereas the reduction in the amount of coal produced leads to avoided impacts. As it can be seen in figures 26 and 27 (below), although the reduction in the production of coal (-5.7 MJ) is less than double the increase in production of natural gas (3.5 MJ), the negative impacts due to the reduction in coal use are 3 times and 2.8 times that of the positive impacts due to the increase in production of natural gas in the human health and ecosystem quality categories, respectively. Petroleum, nuclear and renewables have a minimal effect in the overall indirect impacts (cumulatively less than 2 percent of overall indirect impacts).

In Figure 28, the contribution of each energy carrier to the total direct and indirect impacts is presented. In both direct impacts and indirect impacts, natural gas accounts of the total impacts (28%). For coal, although overall coal use is reduced– leading to avoided indirect impacts – the increase in its price still leads to positive direct impacts. Once more, petroleum, nuclear and renewables have a minimal share in the direct impacts.

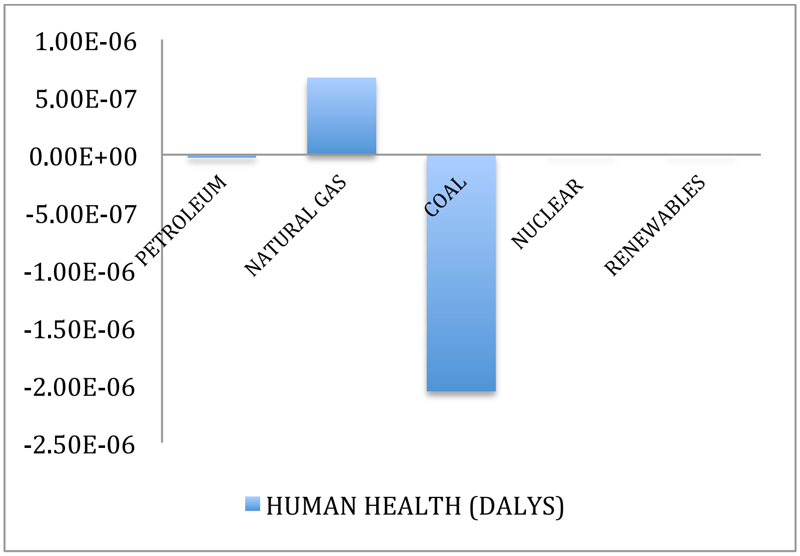

Figure 26 - Indirect impacts on human health in DALYS per MJ of coal dissipated

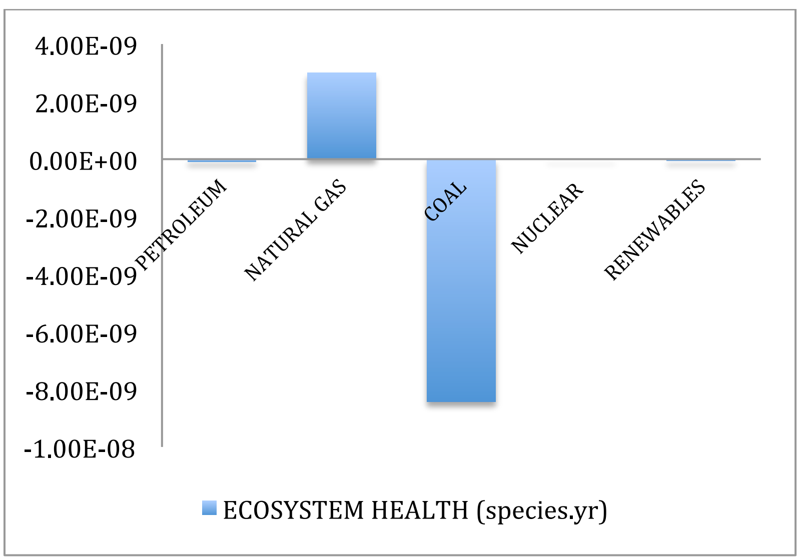

Figure 27 - Indirect impacts on ecosystem health in spercies.yr per MJ of coal dissipated

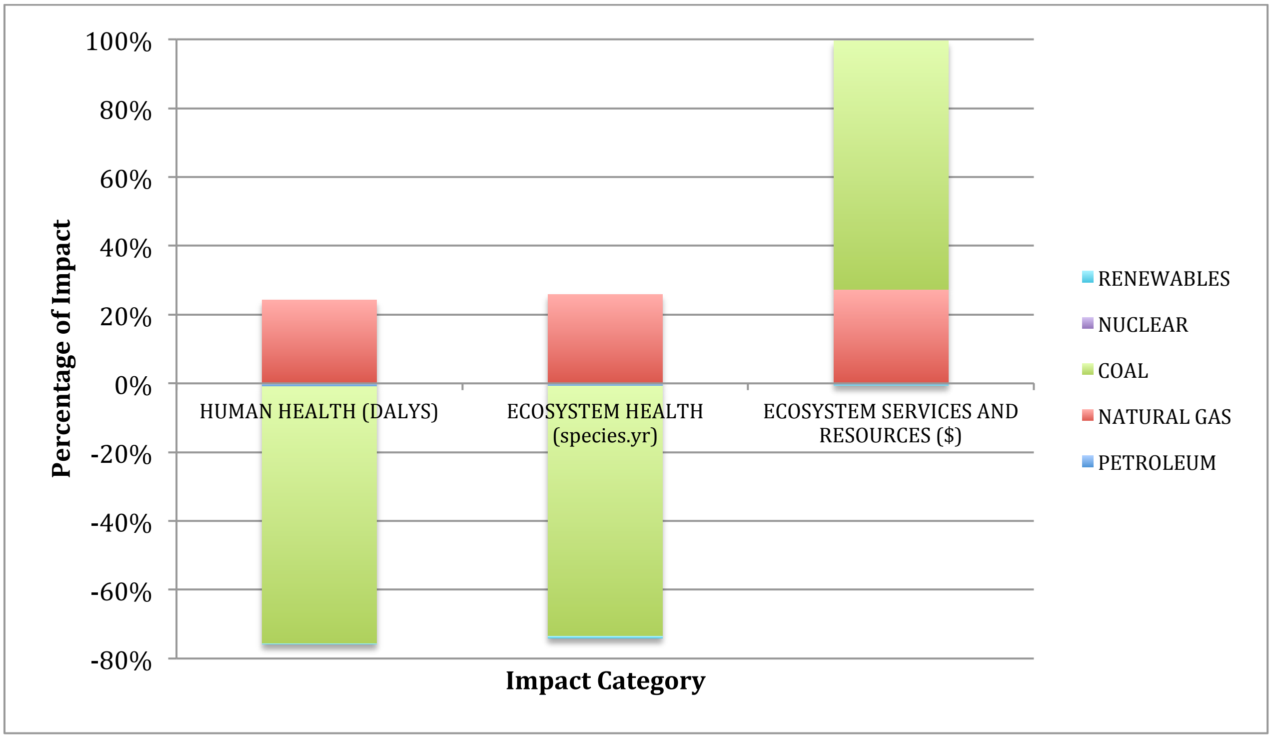

Figure 28 – Contribution of different fossil resources in the indirect impacts (on Human health and ecosystem quality) and direct impacts of fossil resource depletion for 1MJ of coal

3.4 Results evaluation

3.4.1 Comparison of obtained characterization factors

The obtained characterization factors were compared with characterization factors from selected existing LCIA methods.

3.4.1.1 Midpoint characterization factors

Characterization factors for coal and natural gas, relative to petroleum values, are plotted for different LCIA methods in figure 29 (below). LCIA methods included in the graph are CML 2001 and EDIP, as these methods are recommended by the ILCD handbook. To demonstrate the regional discrimination in our method, selected regional examples and the global value for FOCSI are presented.

As it can be seen, in CML 2001 and EDIP, impact factors are ranked from smallest to largest as coal, natural gas, and petroleum. Both of these methods rely on a global reserves-over-production model. This is an expected outcome as reserves over production ratios for fossil resources are ranked similarly. The same relation is observed in the global FOCSI values, which are also based on a global reserves to production model. However, as it can be seen in the same figure, this relation does not necessarily hold true when country-level FOCSIs are studied. In fact, in some countries, all fossil resources are equally scarce (e.g. Canada), while in some countries, coal is scarcer than natural gas (e.g. Qatar), and in other countries, natural gas is scarcer than coal, yet the proportions vary (e.g. United States, Russia, Germany, Japan, and Iran). This exemplifies the added value of regional discrimination in fossil resource depletion impact assessment.

Different FOCSI values for different countries lead to different midpoint and endpoint impact scores, as will be presented in the illustrative examples in section 3.5.

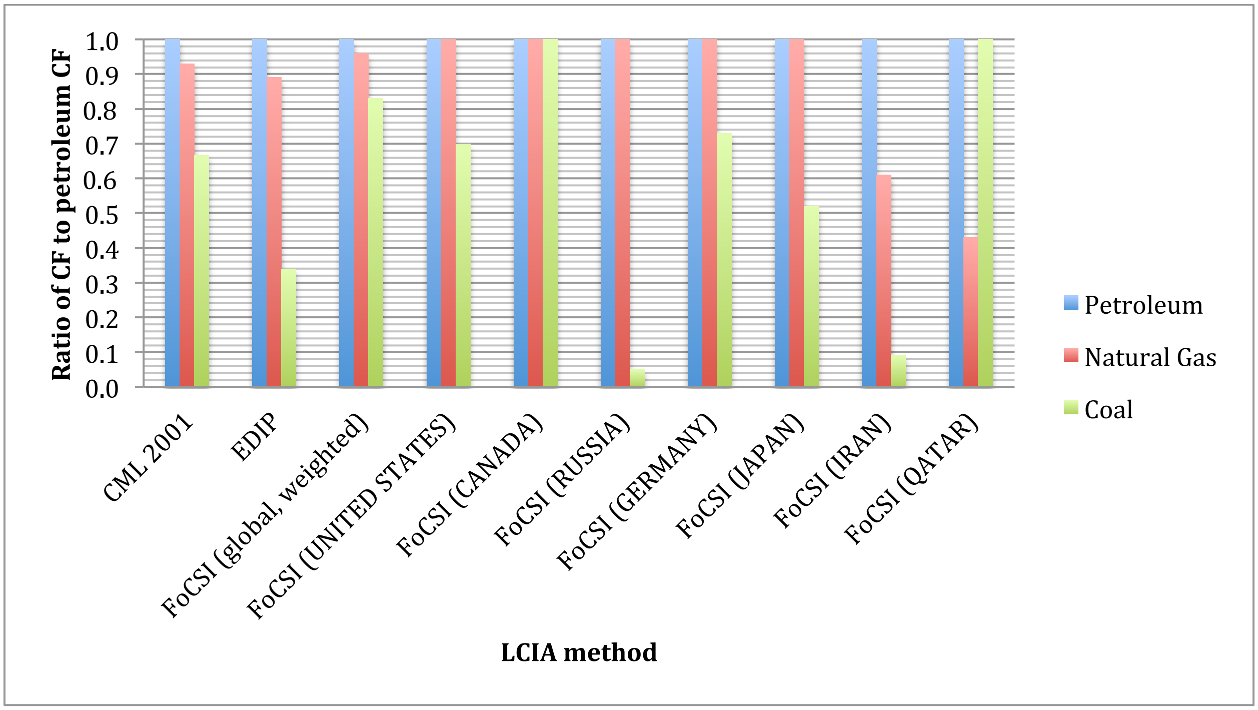

Figure 29 - Comparison of midpoint characterization factors between recommended LCIA methods (CML 2001, EDIP) and FOCSI values from our proposed method.

3.4.1.2 Endpoint characterization factors

The obtained characterization factors were compared with those in ReCiPe in Figure 30. It should be noted that at the time this research was started, ReCiPe was using a characterization factor of 0.382 $/MJ for all fossil resources. In 2012, this number was updated to 0.00393 $/MJ, as presented in Figure 30. The reason for this change was explained as an error in calculation (ReCiPe report update).

In reality, ReCiPe only calculates additional costs for petroleum, and uses the same values for natural gas and coal. The reason behind this assumption, according to ReCiPe, it is considered that the exploitation of natural gas fields is often linked to the exploitation of petroleum as they often occur in the same location. For coal, it is considered difficult to relate extra costs to scarcity, so the same additional costs as those for petroleum are used (Goedkoop et al., 2009).

The global characterization factors for petroleum in our method are a factor of 1.25 higher than those calculated by ReCiPe. For coal, however, the global characterization factors resulting from this research project are smaller by a factor of 7. These results show that discrimination between fossil fuels based on their functionality and substitutability (not done in previous LCIA methods) is pertinent. Unfortunately, it was not possible to calculate endpoint characterization factors for natural gas.

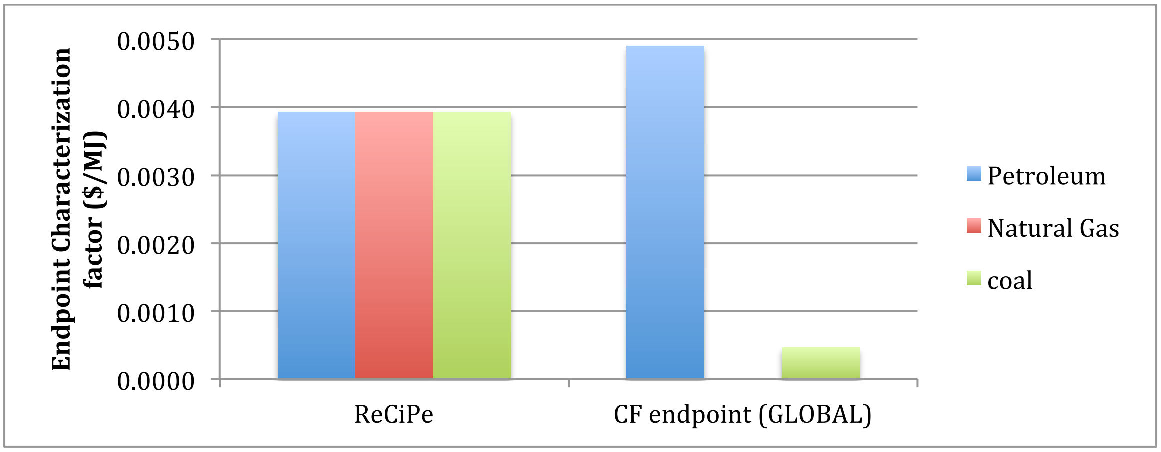

Figure 30 - Comparison of global CFs obtained in this research project versus ReCiPe (revised 2012).

In Figure 31, endpoint characterization factors for coal and natural gas, relative to petroleum values, are plotted for selected existing LCIA methods. The LCIA methods selected are ReCiPe, Impact 2002+, and Ecoindicator. As it can be seen in all methods, there is no discrimination in the characterization factors between fossil resources. This is compared to the global endpoint characterization factors from our research. The ratio between the endpoint characterization factor for petroleum and coal in our method is equal to 0.095. This difference is due to the different FOCSI values, MPIs and TACs for petroleum and coal.

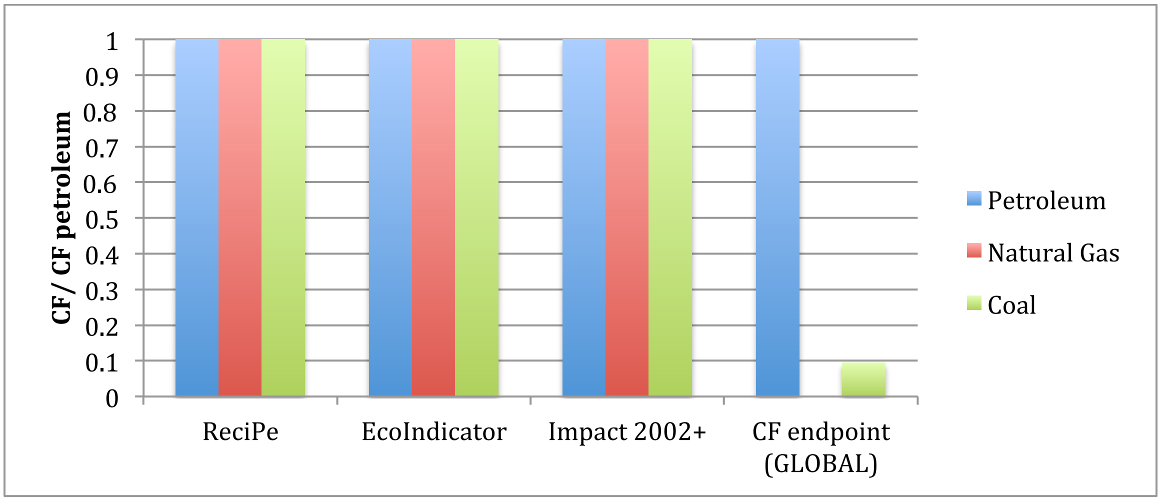

Figure 31 - Comparison of CFs from selected endpoint methods (ReCiPe, EcoIndicator, and IMPACT 2002+) with global CFs from our proposed method

Our proposed method also features regional discrimination. Regionalization applies to coal and natural gas with regards to the FOCSI values for the producing countries. For petroleum, because of the global market assumption, all countries have the same FOCSI value. Because we were not able to calculate endpoint characterization factors for natural gas, we can only present the discrimination ability of our method for coal characterization factors. This is presented in Figure 32, where endpoint characterization factors for coal are presented for selected countries. As it can be seen, characterization factors vary depending on the country where the coal is produced. This difference in the endpoint characterization factors is due to the different FOCSI values, which represent the regional scarcity of coal. In this figure, the endpoint characterization factor for Canada is 20 times higher than that of Russia. The characterization factor for coal can vary between 0.0056 $/MJ for a country with a FOCSI value of 1.0 to zero for a country with a FOCSI value of zero.

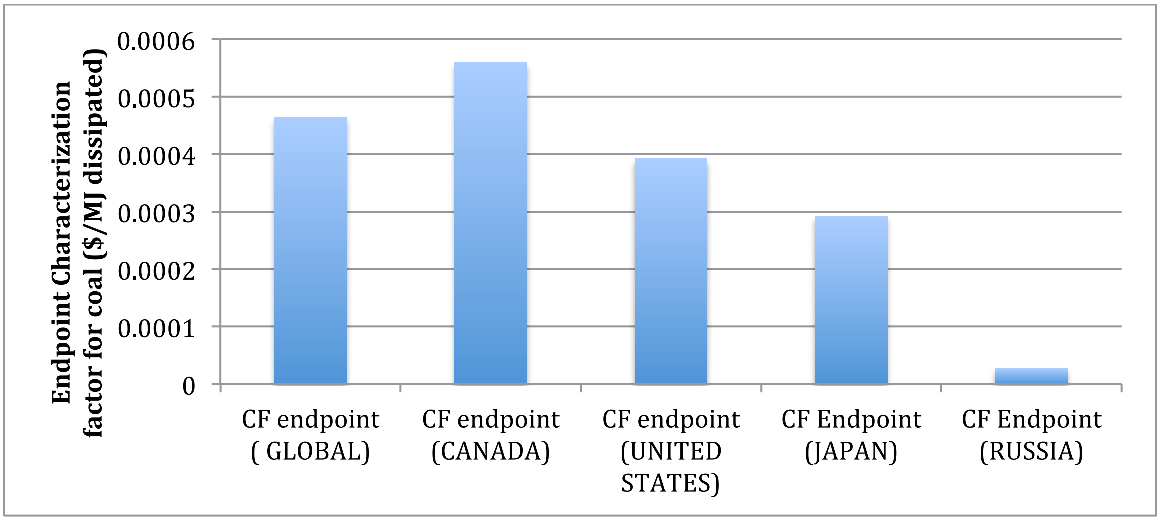

Figure 32 - Endpoint characterization factors for coal for selected countries using our proposed method.

3.4.2 Sensitivity analysis

3.4.2.1 Sensitivity of midpoint characterization factors

The following are tornado charts that demonstrate the sensitivity of FOCSI values to a 25 percent variability in the parameters selected for the sensitivity analysis. The bars show the maximum variation observed in FOCSI values for all countries due to a 25 percent increase or decrease. **Coal -** Figure 33 is the tornado chart for coal FOCSI values.

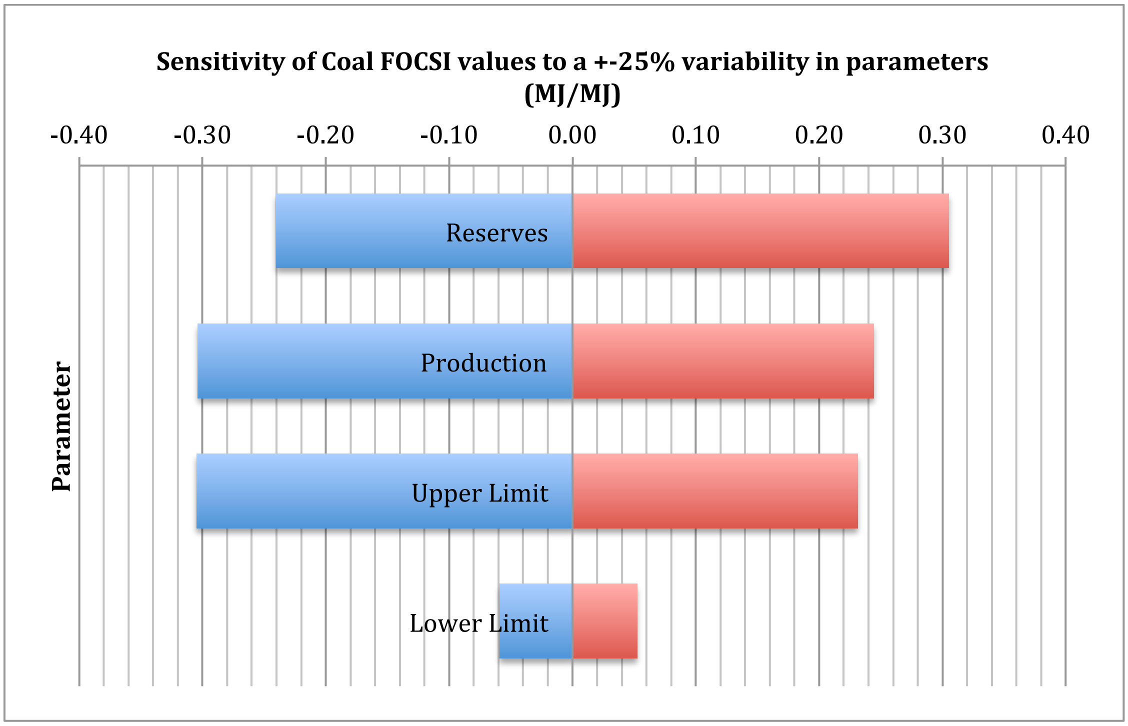

Figure 33 - Maximum sensitivity of Coal *FOCSI* values for different countries to a +-25% variation in parameters

As it can be seen, the FOCSI values for coal are most sensitive to a change in available reserves, with a maximum change of 31 % in FOCSI values. A scenario is explored to determine the impact of using 3P reserves instead of 2P reserves. This scenario is explored in subsection 3.4.2.3.

Production values are found to be the next sensitive parameter. As explained in the methodology, the production values used are those of 2012, which were the most recent available data at the time of calculation of the values. A review of historical production figures for the last 20 years showed that global production values have continued to rise for all three fossil resources. Production figures will continue to rise according to energy forecasts.

Current reserves to current annual production figures are commonly used for calculating the reserves-to production ratios for fossil resources. We have used current reserves to production values. Coal production values used came from the most recent available data, as it is common practice when calculating R/P values. A comparison of coal annual production rates for the last ten years showed that the rates have continued to increase, leading to the most conservative estimates to date. However, since reserves and production are both sensitive parameters, R/P values should be revised accordingly as new production rates become available.

The next sensitive parameter is the upper limit (UL) used in the calculation of FOCSI values. A maximum 30 percent is observed in FOCSI values. The lower limit (LL) has a smaller effect on results, since more reserves-to-production values tend to be closer to UL. A scenario is studied where instead of the two upper time horizons used in the IPCC guidelines, we use the short and medium term time horizons of 20 and 100 years to calculate FOCSI values. This scenario is presented in subsection 3.4.2.5.

Reserves-to-production values are identified as the most sensitive parameter, emphasizing the importance of using reliable sources for data. Reserves-to-production values tend to change over time due to unpredictable circumstances; however they are used as a relevant indicator for scarcity in many studies.

Natural Gas - Figure 34 presents the tornado chart for natural gas FOCSI values. The bars for each parameter show the maximum variation observed in FOCSI values for all countries as a consequence of a 25 percent variation (increase or decrease) in values.

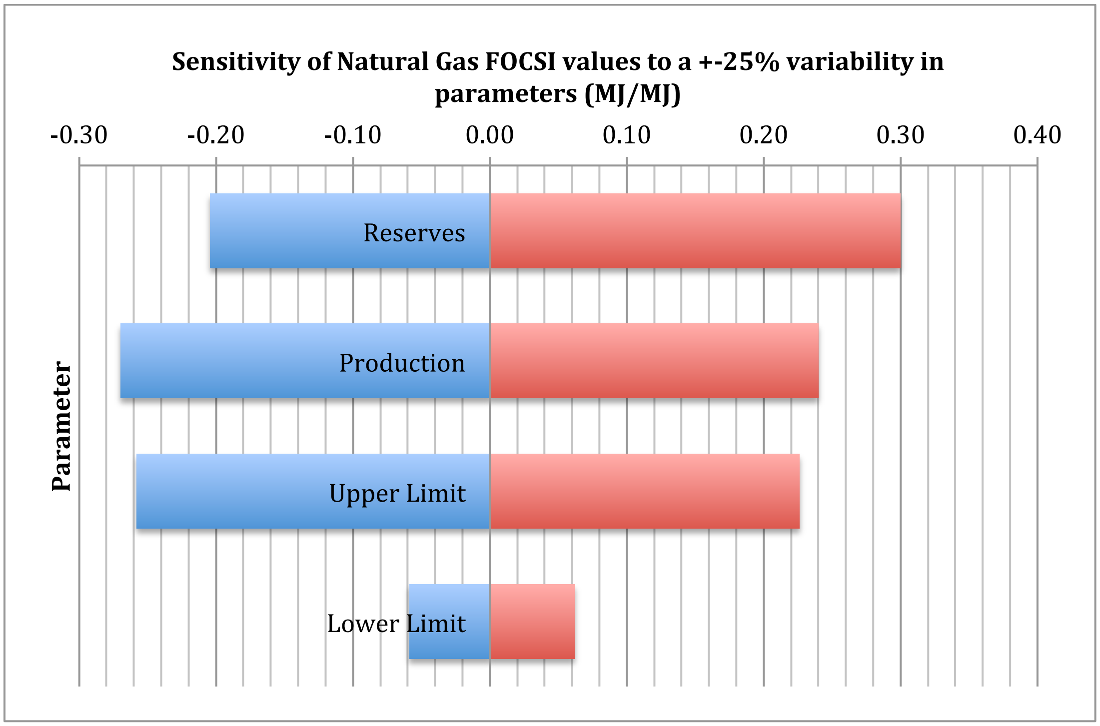

Figure 34-Sensitivity of natural gas *FOCSI* values to a +-25% variation in parameters

A similar trend as coal was observed in the ranking of the parameters based on sensitivity. A 25 percent change in reserves values can have a maximum of a 30 percent effect on results, followed by production, UL, and LL with maximum changes of 27, 26 and 6 percent respectively.

Petroleum- With a reserves-over-production ratio of 62.7 years, the petroleum FOCSI value of 1.0 MJ/MJ showed no sensitivity to a change of 25 percent to the LL, UL, reserves and production parameters.

In scenarios #1 and #2, presented in subsections 3.4.2.4 and 3.4.2.5, we present the impact of using a 20-100 year time horizon and using 3P reserve estimates. These scenarios present an interesting insight into the chosen values for our parameters.

3.4.2.2 Sensitivity of endpoint characterization factors

Petroleum - The tornado chart representing the sensitivity of endpoint characterization factors to the selected parameters is presented in Figure 35 (below). As explained in the previous section, the petroleum FOCSI value did not show any sensitivity to a 25 percent change in the values for the selected parameters studied.

The beta value, used in calculating MPI, is found to be a very sensitive number, affecting the endpoint characterization factor by 33 percent. A simplification was used in our study to use a beta value of -0.15 globally for petroleum, as done in previous work found in the literature. A more detailed study can be performed in the future where beta values for each region or country are assessed and used in calculations.

Because of the way the MPI formula is defined, used reserves values affect the endpoint characterization factor greatly, up to 29%. This is far greater than the sensitivity of results to total available reserves (up to 5 percent). There is a smaller uncertainty associated with the values for used reserves than there is with total reserves.

In calculating the TAC values, the number of years to calculate the total costs is a crucial parameter. We have used 20 years as the number of years for which total costs should be accounted for. As expected, the number of years used in modeling can have a major impact on TAC values. The results show the effect of using 15 years (-25%) for calculating total casts resulted in a 27 percent reduction in the characterization factor value. Using linear interpolation, we estimated the costs after the 20 year period. Results showed that using 25 years (+25 percent) for calculating the total costs led to a 28 percent increase in the endpoint characterization factor. As explained in the methodology, the number of years chosen is a parameter that is limited by the model that is used (WEPS+). It is possible that other models may exist that calculate costs for a higher number of years.

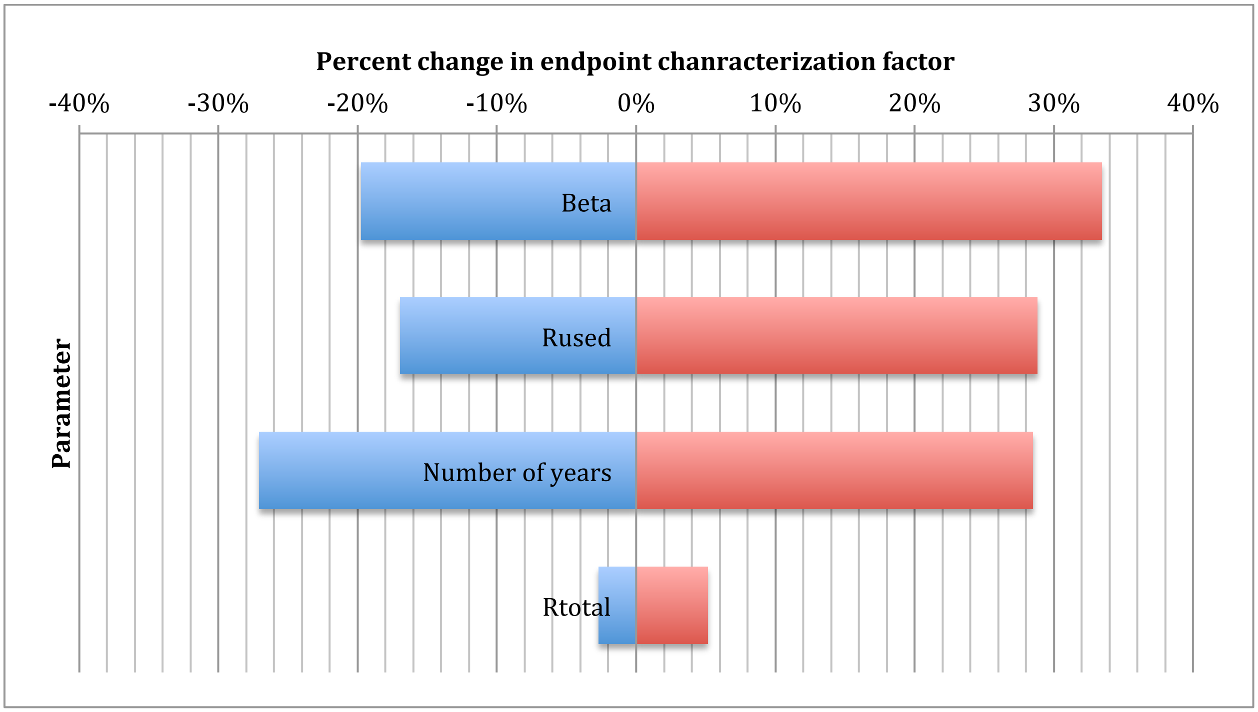

Figure 35 - Sensitivity of Petroleum endpoint characterization factor to a 25 percent shift in parameters

Figure 36 presents the tornado chart for all the parameters that are selected for the sensitivity analysis of the endpoint characterization factors for coal. As it was observed, the number of years used in the calculation of the TAC parameter had the greatest impact on the endpoint characterization factors, with a maximum impact of 40 percent. Beta values are ranked next, with a maximum effect of 33 percent, once again emphasizing the future possibilities of using regional beta values in calculations.

Annual production rates and the upper limit were the next two most sensitive parameters affecting FOCSI values (see section 3.4.2.1). Similar to petroleum, used reserves were more sensitive than total available reserves values used in the beta calculations. The least sensitive parameter studied was the lower limit.

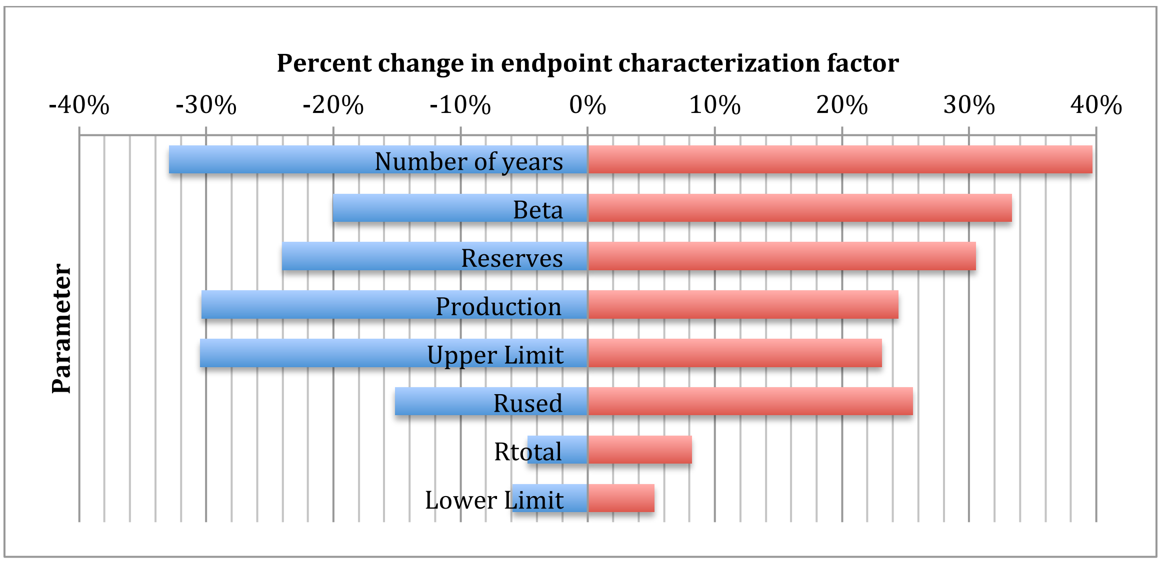

Figure 36 - Sensitivity of coal endpoint characterization factors to a 25 percent change in parameters

3.4.2.3 Scenario #1 – Time horizons

This scenario studied the effect of replacing the two upper time horizons in the IPCC guidelines (reference) with the short and medium term time horizons of 20 and 100 years respectively to calculate our midpoint and endpoint characterization factors. The results are presented below.

Coal – FOCSI values changed considerably in this scenario, with an average reduction in FOCSI values in all countries by 30 percent (standard deviation of 30 percent). The maximum change observed in FOCSI values was 1.0 MJ/MJ (observed for Italy, with an R/P ratio of 100.1 years). The global FOCSI value for coal in this case becomes 0.40 MJ deprived / MJ dissipated.

Sixty seven percent of the countries with coal reserves have a reserves-to-production ratios greater than 100 years. The results were therefore expected to change considerably as the upper and lower limits in FOCSI calculations were changed. The endpoint characterization factors for coal are affected equally.

Natural Gas – Natural gas FOCSI values changed considerably in this scenario. On average, FOCSI values were reduced by 0.2 MJ/MJ (standard deviation of 0.3 MJ/MJ). The maximum changed observed was 1.0 MJ/MJ (observed for Senegal, with an R/P value of 100.1 years). The global FOCSI value for natural gas with these time horizons used is equal to 0.65 MJ deprived / MJ dissipated.

Sixty seven percent of the countries with natural gas reserves have reserves-to production ratios greater than 100 years. As for coal, these results were expected.

Petroleum – For petroleum, the global reserves-to-production value of 62.7 years led to the FOCSI value to 0.47 MJ deprived /MJ consumed using the new time horizons. This new value is less than half of the FOCSI value of 1.0 MJ/MJ that we calculated using the time horizons of 100 and 500 years. The endpoint characterization factor for petroleum is affected equally.

Our philosophy for using a time line of 100 and 500 years is explained in the methodology section. We believe that for an important and vital resource like fossil resources, a reserves-over-production ratio of 100 years is not enough to consider a resource abundant enough to not deprive future users.

Results from this scenario study, however, emphasize the importance of choosing time horizons that are representative of the concerns that we currently have about resource depletion. According to the level of optimism towards future technologies, discoveries, alternatives, etc., one can use different time horizons. As seen in this scenario study, this can lead to different characterization factors. ReCiPe and EcoIndicator allow for this difference in choices by offering three different perspectives in their LCIA methodology. These methods allow users to choose either perspectives according to their personal philosophy, though one is recommended. Each perspective offers different time horizons (short, medium, or long) with characterization factors for that perspective.

3.4.2.4 Scenario #2 – reserves estimates

This scenario explores the impact of replacing 3P reserves with 2P reserves in the reserves-over-production calculations. The results are presented below.

Coal – Using 3P reserves for coal resulted in a change in FOCSIs for four countries: a change of -0.7 MJ/MJ for the United States, a change of -0.37 for Australia, a change of -0.29 MJ/MJ for Hungary, and a change of -0.04 MJ/MJ for South Korea.

Globally, the possible reserves for coal are 0.9 times the global 2P reserves and therefore a considerable addition to the global available reserves. In most cases however, these resources are added to countries that already have a FOCSI value of 1.0 MJ/MJ and therefore no changes are made in final results. When one considers 3P reserves, a global weighted FOCSI value of 0.69 MJ/MJ is yielded.

Natural Gas – Adding 3P reserves to reserves estimates for natural gas led to changes in FOCSI values for two countries: a change of -0.20 MJ/MJ for Peru and a change of -0.55 MJ/MJ for Kazakhstan.

3P reserves additions added only 6 percent to global available reserves and therefore do not contribute significantly to Natural Gas FOCSI results. The global weighted FOCSI value considering 3P reserves for natural gas is calculated as 0.93 MJ/MJ.

Petroleum- Using 3P reserves for petroleum leads to a global reserves over production of 212 years, resulting in a FOCSI value of 0.7 MJ/MJ.

It should be noted that 3P reserves are estimates of available reserves with a 95 percent chance of not being exceeded, so there is a relatively higher uncertainty associated with using these values. It was difficult to find reliable 3P data that is available to the public, as companies do not report 3P values. Only one reference was found and used for 3P data, therefore it wasn't possible to cross-check our data. Using more reliable references for 3P data is recommended in future work.

3.5 Illustrative example

3.5.1 Impact at midpoint

The objective of the illustrative example is to evaluate the model by presenting a concrete example of how the proposed characterization factors can be used to calculate direct impacts at midpoint and endpoint as well as indirect impacts. The results are interpreted and compared with those from EDIP and CML at midpoint and with ReCiPe at endpoint. Through these examples, the contribution of the intermediary parameters in the model is discussed, and the added value of the new model is explored.

High coal, natural gas, or petroleum-consuming and importing countries (BP, 2012) were selected for this exercise. The supply mix for each country is derived based on import, export, and production data. The selected countries along with their supplying countries and supply shares are presented in Tables 12 and 13 for coal and natural gas respectively. For petroleum, no specific country is chosen since the characterization factors apply to all countries.

Table 19 – Selected countries and supply mixes for coal example

Selected country	Supply mix of coal	
	Source Country	Supply share
China	China	95.6%
	Indonesia	1.45%
	Australia	1.67%
	South Africa	0.54%
	Russia	0.31%
India	India	88.3%
	Indonesia	3.9%
	South Africa	3.9%

	Australia	3.9%
United States	United States Canada	98.0% 2.0%
Japan	Japan Australia	1.0% 99.0%
Russia	Russia Kazakhstan	87.5% 12.5%

Table 20 – Selected countries and supply mixes for natural gas example

Selected country	Supply mix of Natural Gas	
	Source Country	Supply share
United States	United States Canada Mexico	83.9% 15.9% 0.2%
Russia	Russia Azerbaijan Kazakhstan Turkmenistan Uzbekistan	98.07% 0.04% 0.71% 0.57% 0.61%
United Arab Emirates	UAE Qatar	71.33% 28.76%

Iran	Iran Azerbaijan Turkmenistan	95.76% 0.22% 4.03%
Qatar	Qatar	100%

We calculate the impacts due to the dissipation of 1 MJ of coal, natural gas, and petroleum at midpoint in these countries using EDIP, CML, ReCiPe and our method. The results are presented in Tables 20, 21 and 22 for coal, natural gas, and petroleum respectively.

CML 2002 assesses the depletion of all resources compared to the reference metal antimony. The depletion of 1 MJ of coal causes an impact of 4.57×10^{-4} kilograms of antimony equivalent. The depletion of 1 MJ of natural gas causes an impact of 5.34×10^{-4} kilograms of antimony equivalent. For petroleum, the impact is equal to 4.90×10^{-4} kilograms of antimony equivalent. Although these values provide the relative scarcity in comparison to antimony which is a very scarce metal [R/P of 13 years according USGS (2011) to they do not address the problem caused by scarcity, which is how the availability of the resource for future users will be affected.

EDIP 97 calculates the impacts from resource use according to how much of the allocated reserves for each world citizen is used. In the case of coal, each MJ of coal is 4.56×10^{-7} person-reserve equivalent. For natural gas, this value is equal to 1.40×10^{-7} person-reserve equivalent and for petroleum, it is equal to 9.65×10^{-7} person-reserve equivalent. Although these values are a good indication of how much of a resource is being used in comparison to what an average world citizen consumes annually, it is still not an indication of the scarcity of the resource, which should address how future users will respond to the reduction of available resources.

The impact due to the dissipation of 1MJ of coal, natural gas, and petroleum are calculated using our method and presented in the last column in tables 21, 22 and 23. The impact is calculated by multiplying the amount of resource dissipated ,in this case 1MJ, by the sum of the product of FOCSI values of supplying countries by their supply share:

$$Impact = Resource\ dissipated\ (MJ)\times \sum Supply\ share_i\ (\%)\times FOCSI_i\ (\frac{MJ\ deprived}{MJ\ dissipated})$$ Equation 16

As can be seen, the impacts from the depletion of coal are different based on the country where the coal is consumed. China, for example, which produces most of its coal domestically, has a coal FOCSI value of 1 MJ/MJ. The consumption of 1 MJ coal in China therefore leads to depriving future users of 0.98 MJ of coal. Russia on the other hand, has abundant coal resources, and the dissipation of 1MJ leads to a 0.1 MJ deprivation for future users. As can be seen, the supply mix plays a major role in the magnitude of the impact. Japan, for example, imports most of its coal from Australia, and therefore dissipation of a resource has less of an impact on future users (0.37 MJ deprived/MJ dissipated) than if Japan used local coal (0.52 MJ deprived/MJ dissipated).

Table 21 - Impact at midpoint due to the dissipation of 1 MJ of coal calculated using selected LCIA methods and proposed methodology

Selected Country	CML 2002	EDIP 97	**Proposed method**
China	4.57×10^{-4}kg Sb eq.	4×10^{-7}pers. res. eq.	0.98 MJ deprived
India			0.94 MJ deprived
United States			0.71 MJ deprived
Japan			0.37 MJ deprived
Russia			0.10 MJ deprived

Using our proposed method, the impacts due to the depletion of natural gas are different depending on in which country they are being consumed. The dissipation of 1 MJ of natural gas in the United States or Russia both lead to 1 MJ deprivation for future users. The impacts associated with the dissipation of 1 MJ of natural gas in Qatar on the other hand, are less than half of that in the United States or Russia, leading to 0.43 MJ deprivation for future users.

Table 22 - Impact at midpoint due to the dissipation of 1 MJ of natural gas calculated using selected LCIA methods and proposed methodology

Selected Country	CML 2002	EDIP 97	**Proposed method**
United States	5.34×10^{-4}kg Sb eq.	1.4×10^{-6}per. res. eq.	1.00 MJ deprived
Russia			1.00 MJ deprived
U.A.E.			0.79 MJ deprived
Iran			0.62 MJ deprived
Qatar			0.43 MJ deprived

For petroleum, using the proposed method, the impacts associated with the dissipation of 1 MJ of petroleum is independent of where it is consumed. Due to the fact that global reserves to production ratio for petroleum is less than 100 years, the dissipation of 1 MJ of petroleum leads to depriving future users of 1 MJ of petroleum.

Table 23 - Impact at midpoint due to the dissipation of 1 MJ of petroleum calculated using selected LCIA methods and proposed methodology

Selected Country	CML 2002	EDIP 97	**Proposed method**
Any country	4.90×10^{-4}kg Sb eq.	9.7×10^{-7}per. res. eq.	1.00 MJ deprived

The proposed method is the first to characterize the impacts at midpoint by accounting for deprivation for future users, and this is considered an added value to previous LCIA methods. Moreover, as shown in the examples above, regional discrimination leads to different impacts based on where the resource is being used, which is an added value to previous methods which do not apply regional discrimination.

3.5.2 Impact at endpoint

Impact at endpoint is calculated as:

$$Impact = Resource\ dissipated\ (MJ)\times\left[\sum\ Supply\ share_i\ (\%)\times FOCSI_i\left(\frac{MJ\ deprived}{MJ\ dissipated}\right)\right]\times MPI\left(\frac{\$/MJ}{MJ\ deprived}\right)\times TAC\left(\frac{\$}{\$/MJ}\right)$$ Equation 17

Table 23 presents the impacts at endpoint for the consumption of 1MJ of coal in selected countries. As can be seen, impacts due to the use of 1MJ change by a factor of close to ten between China and Russia. The impact as a consequence of the dissipation of 1 MJ of coal ranges from 5.58×10^{-5} to 5.47×10^{-4} dollars. Using ReCiPe, the impact of the dissipation of 1 MJ of coal for all countries would be equal to 3.93×10^{-3} dollars.

Table 24 presents the impacts at endpoint for the consumption of 1MJ of petroleum calculated using the proposed methodology. The impact is the same regardless of where the users are, and equal to a value of 4.97×10^{-3} dollars. Using ReCiPe, this impact would be equal to 3.93×10^{-3} dollars.

Table 24 - Impact at endpoint due to the dissipation of 1 MJ of coal calculated using proposed methodology

Selected Country		Proposed Method			ReCiPe
	$\sum supply\ share\times FOCSI$ $\left(\frac{MJ\ deprived}{MJ\ dissipated}\right)$	MPI $\left(\frac{\$/MJ}{MJ\ deprived}\right)$	TAC $\left(\frac{\$}{\$/MJ}\right)$	Impact ($)	Impact ($)
China	0.98 MJ/MJ	1.69×10^{-21}	3.30×10^{17}	5.47×10^{-4}	3.93×10^{-3}
India	0.94 MJ/MJ	1.69×10^{-21}	3.30×10^{17}	5.24×10^{-4}	
United States	0.71 MJ/MJ	1.69×10^{-21}	3.30×10^{17}	3.96×10^{-4}	
Japan	0.37 MJ/MJ	1.69×10^{-21}	3.30×10^{17}	2.06×10^{-4}	
Russia	0.10 MJ/MJ	1.69×10^{-21}	3.30×10^{17}	5.58×10^{-5}	

Table 25 - Impact at endpoint due to the dissipation of 1 MJ of petroleum calculated using the proposed methodology

Selected Country	Proposed Method				ReCiPe
	$FOCSI\,(\frac{MJ\ deprived}{MJ\ dissipated})$	MPI $(\frac{\$/MJ}{MJ\ deprived})$	TAC $(\frac{\$}{\$/MJ})$	Impact ($)	Impact ($)
All countries	1.00	5.20×10^{-20}	9.56×10^{16}	4.97×10^{-3}	3.93×10^{-3}

3.5.3 Indirect Impacts

The indirect impacts are calculated as:

$$Indirect\ Impacts = Resource\ dissipated\ (MJ\ )\times\left[\sum\ \ Supply\ share_i\ (\%)\times FOCSI_i\left(\frac{MJ\ deprived}{MJ\ dissipated}\right)\right]\times MPI(\frac{\$/MJ}{MJ\ deprived})\times\sum Impact(TACON_i)$$ Equation 18

The results are presented in table 25 for the indirect impacts associated with the dissipative use of 1 MJ coal. As it can be seen, regional discrimination leads to a change of up to an order of magnitude in the indirect impacts between China and Russia.

Table 26 presents the indirect impacts associated with the dissipative use of 1 MJ of petroleum, regardless of where it is being used.

Table 26 - Indirect impacts associated with the dissipation of 1 MJ of coal

Selected Country	Proposed Method	
	$\sum supply\ share\ \times FOCSI$ $(\frac{MJ\ deprived}{MJ\ dissipated})$	Indirect Impact
China	0.98 MJ/MJ	-1.38×10^{-6}DALYS Human Health
		-5.46×10^{-9} species.yr Ecosystem Health
India	0.94 MJ/MJ	-1.33×10^{-6}DALYS Human Health
		-5.24×10^{-9} species.yr Ecosystem Health
United States	0.71 MJ/MJ	-1.00×10^{-6}DALYS Human Health
		-3.95×10^{-9} species.yr Ecosystem Health
Japan	0.37 MJ/MJ	-5.22×10^{-7}DALYS Human Health
		-2.06×10^{-9} species.yr Ecosystem Health
Russia	0.10 MJ/MJ	-1.41×10^{-7}DALYS Human Health
		-5.57×10^{-10} species.yr Ecosystem Health

Table 27 - Indirect impacts associated with the dissipation of 1 MJ of petroleum

Selected Country	Proposed Method	
	$\sum supply\ share\ \times FOCSI$ $(\frac{MJ\ deprived}{MJ\ dissipated})$	Indirect Impact
All countries	1.00 MJ/MJ	-5.39×10^{-6}DALYS Human Health
		-2.47×10^{-8} species.yr Ecosystem Health

CHAPTER 4 CONCLUSIONS

The objective of this study was to develop a new LCIA methodology for fossil resources depletion based on a functional perspective, and to calculate midpoint and endpoint characterization factors and indirect impacts for fossil resources depletion in a regionalized manner, while accounting for resource substitutability and user adaptability.

This section explains the general conclusions of the research project and certain methodological suggestions as well as recommendations for future work.

At the completion of this research, a new framework has been developed for life cycle impact assessment of fossil resources depletion using the functional perspective. Midpoint and endpoint characterization factors and indirect impacts have been calculated for fossil resources.

At midpoint, a significant difference is observed in the calculated amount of resource deprived from future users due to the dissipation of a resource based on where the users are located. Our proposed method uses this concept in calculating midpoint and endpoint characterization factors. A comparison of our characterization factors with those of other methods at midpoint shows that although at a global level, our model follows the same ranking in fossil resource characterization factors as other recommended methods, at a regional level, our characterization factors do not necessarily follow the same global ranking, because some resources are more abundant in certain regions of the world. This is the added value of our methodology.

At endpoint, a significant difference is observed in the total additional costs due to the depletion of a fossil resource depending on the type of fossil resource (petroleum, coal, natural gas) and on the country where users are located. Our proposed method uses this regional and resource differentiation in endpoint and indirect impacts calculation. A comparison with previous methods shows that at endpoint, the method developed within this research work allows regional discriminating power at country level (a difference of a factor between 0 and 1.0 could exist depending on regional availability) and provides results differentiated for each fossil resource (a difference by a factor of 10 exists between the petroleum and coal global endpoint characterization factors). Our model also takes into account the effect of substitution among fossil resources and among alternative energy sources (nuclear, renewables) according to their application, and the effect of elasticity between price and demand.

For indirect impacts, it was observed that for both petroleum and coal, the calculated indirect impacts had negative values, i.e. they were “avoided impacts”. The fact that the values were negative was due to a combination of factors. These include the transition to alternative resources which in this case were cleaner resources as well (in the example of coal being replaced by natural gas in the electricity sector) and a reduction in consumption as a result of an increase in price (in the case of petroleum). One could be interpret this as meaning that increasing the scarcity of a certain fossil resource by extracting it may have positive indirect impacts on the environment (through the process of making that resource more expensive and eventually driven out of the market by cleaner alternatives). This is not an acceptable interpretation, since in most cases the extracted fossil resources will be used in an application where they are combusted, and the impacts from fossil resources due to their consumption and disposal, which are under other impact categories, should be considered.

It is observed that the most sensitive parameters for the calculation of the midpoint characterization factors are reserves-to-production ratios and the upper limit used in calculating FOCSI values. The two scenarios with alternative values/assumptions are used to evaluate our FOCSI values. Endpoint characterization factors are sensitive to beta, a parameter used in the curve-fitting model to calculate the marginal price increase. The number of years used to define the endpoint impacts and indirect impacts (20 years was used in this study) is another important sensitive parameter.

This work contributes to the enhancement of the LCIA methodology for the impacts associated with the depletion of fossil resources in LCA by increasing the discrimination power of impact assessment between fossil resources and for different countries, and by accounting for issues such as substitutability and changes in demand. Fossil resource depletion in LCA accounts for a great portion of the impacts in the resource use impact category. This work will contribute towards developing the midpoint and endpoint characterization factors used in IMPACT World+ impact assessment method.

RECOMMENDATIONS FOR FUTURE WORK

For the sensitive parameters identified that were obtained from databases, it is recommended that more databases are sought in order to reduce uncertainty in the results. Parameters such as reserves and annual production rates can be updated on a regular basis to minimize errors in results.

A factor that can change future production rates of fossil resources, and therefore future adaptation scenarios, is the policy changes that may be occurring in the future. Our model has performed this analysis based on the forecast presented by the USEIA in their 2011 World Energy Outlook. Other scenarios could be studied where there would be additional taxes or production caps on certain fuels, resulting in modifications to the characterization factors.

The WEPS+ model was found to be a very effective tool in carrying out the objectives of this research. It would be interesting however to compare results from the WEPS+ model with another energy model such as TIMES, or other general equilibrium models such as GTAP, both of which have been used previously for consequential LCA studies (Dandres et al, 2012).

Unfortunately, due to technical difficulties with the WEPS+ software, the direct and indirect impacts were not calculated for natural gas. We expect that natural gas depletion will affect the market differently than the depletion of petroleum or coal, so it is recommended that natural gas depletion characterization be addressed in future work.

Our impact pathway was defined based on a marginal price increase due to a reduction in the availability. This pathway allows for the definition of a region-specific midpoint indicator that then leads to the development of a regional endpoint indicator. An alternative pathway may be chosen where the impacts of extracting an additional amount of a fossil resource are directly calculated using the energy forecast model. This was not possible to test in the WEPS+ modeling software. It would be interesting to compare this study in a different model and compare the results from the two models.

CHAPTER 5 BIBLIOGRAPHY

Alternative Fuels Data Center (n.d.) Retrieved March, 2013, from http://www.afdc.energy.gov/

Canadian Association of Petroleum Producers (CAPP). (2012). *Upstream Dialogue - The facts on Natural Gas*.

Andrews, D. (2010). The difference between LCV and HCL (or Lower and Higher Heating Value, or Net and Gross) is clearly understood by all engineers. There is no 'right' or 'wrong' definition.

Baumann, H., & Tillman, A. (2004). *The Hitch Hiker's Guide to LCA: An Orientation in Life Cycle Assessment Methodology and Application*. Sweden: Studentlitterature.

Bayart, J.-B., Bulle, C., Deschênes, L., Margni, M., Pfister, S., Vince, F., et al. (2010). A framework for assessing off-stream freshwater use in LCA. *The International Journal of Life Cycle Assessment, 15*(5), 439-453.

Bentley, R. W., Mannan, S. A., & Wheeler, S. J. (2007). Assessing the date of the global oil peak: The need to use 2P reserves. *Energy Policy, 35*(12), 6364-6382.

Bösch, M. E., Hellweg, S., Huijbregts, M. A. J., & Frischknecht, R. (2006). Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. *The International Journal of Life Cycle Assessment, 12*(3), 181-190.

Boulay, A. M., Bulle, C., Bayart, J. B., Deschenes, L., & Margni, M. (2011). Regional Characterization of Freshwater Use in LCA: Modeling Direct Impacts on Human Health. *Environmental Science & Technology, 45*(20), 8948-8957.

BP. (2011). *Statistical review of world energy 2011*.

Brandt, A. R. (2010). Review of mathematical models of future oil supply: Historical overview and synthesizing critique. *Energy, 35*(9), 3958-3974.

Brandt, A. R. (2011). *ROMEO model Documentation*: Department of Energy Resources, Stanford University.

Brandt, A. R., Plevin, R. J., & Farrell, A. E. (2010). Dynamics of the oil transition: Modeling capacity, depletion, and emissions. *Energy, 35*(7), 2852-2860.

D & R International, Ltd. (2012). *2011 Buildings Energy Data Book.* Prepared for Energy Efficiency and Renewable energy in the US Department of Energy.

Dandres, T., Gaudreault, C., Tirado-Seco, P., & Samson, R. j. (2012). Macroanalysis of the economic and environmental impacts of a 2005,Äì2025 European Union bioenergy policy using the GTAP model and life cycle assessment. *Renewable and Sustainable Energy Reviews, 16*(2), 1180-1192.

Deffeyes, K. S. (2009). *Hubbert's peak: The impeding world oil shortage*. Princeton, New Jersey: Princeton University Press.

Dewulf, J., Bösch, M. E., Meester, B. D., Vorst, G. V. d., Langenhove, H. V., Hellweg, S., et al. (2007). Cumulative Exergy Extraction from the Natural Environment (CEENE): a comprehensive Life Cycle Impact Assessment method for resource accounting. *Environmental Science & Technology, 41*(24), 8477-8483.

Dreyer, L. C., Niemann, A. L., & Hauschild, M. Z. (2003). Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. *The International Journal of Life Cycle Assessment, 8*(4), 191-200.

Earles, J., & Halog, A. (2011). Consequential life cycle assessment: a review. *The International Journal of Life Cycle Assessment, 16*(5), 445-453.

Ecoinvent. (2013). Introduction to ecoinvent Version 3 for Existing Users. Retrieved June 15, 2013, from http://www.ecoinvent.org/database/ecoinvent-version-3/introduction/.

Ekvall, T., & Weidema, B. (2004). System boundaries and input data in consequential life cycle inventory analysis. *The International Journal of Life Cycle Assessment, 9*(3), 161-171.

Enerdata. (2009). *Energy Scenarios, Technology development and climate policy analysis with the POLES modelling system*.

EUROSTAT. (2007). *Economy-wide Material Flow Accounting- A compilation guide*: Eurostat and the European Commission.

Farrell, A. E., & Brandt, A. R. (2006). Risks of the oil transition. *Environmental Research Letters, 1*(1), 014004.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., et al. (2009). Recent developments in Life Cycle Assessment. [Research Support, Non-U.S. Gov't

Review]. *Journal of environmental management, 91*(1), 1-21.

Frischknecht, R. (2007). *Ecoinvent overview and methodology*.

Goedkoop, M., Heijungs, R., Huijbregts, M. A. J., De Schryver, A., Struijs, J., & van Zelm, R. (2009). *ReCiPe 2008- A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and endpoint level*.

Goedkoop, M., & Spriensma, R. (2000). *The Eco-indicator 99- A damage oriented method for LCIA*. Amersfoot, Netherlands: Pre Consultants.

Graedel, T. T. A., B.R. (2003). *Industrial Ecology*. New Jersey: Prentice Hall.

Greene, D. L. (2003). *Running out of and into: Analyzing Global Oil Depletion and Transition through 2050.*

Greene, D. L., Hopson, J. L., & Li, J. (2006). Have we run out of oil yet? Oil peaking analysis from an optimist's perspective. *Energy Policy, 34*(5), 515-531.

Guinee, J. B., & Heijungs, R. (1995). A proposal for the definition of resource equivalency factors for use in product life‚Äêcycle assessment. *Environmental Toxicology and Chemistry, 14*(5), 917-925.

IEA. (2009). *International Energy Agency's World Energy Outlook 2009*.

IEA. (2012). *Energy Technologies Perspective 2012: Pathways to a clean energy system*.

ILCD. (2010a). *ILCD Handbook- Framework and Requirements for LCIA models and indicators*: European Commission-Joint Research Center-Institute for Environment and Sustainability.

ILCD. (2010b). *ILCDHandbook - Analysis of Existing Environmental Impact Assessment Methodologies for use in LCA*: European Commission-Joint Research Center-Institute for Environment and Sustainability.

ILCD. (2011). *ILCD Handbook- Recommendations based on existing environmental impact assessment models and factors for LCA in a European Context*: European Commission-Joint Research Center-Institute for Environment and Sustainability.

IMPACT World+ (2013). *What is IMPACT World+?*. Retrieved June 25, 2013 from IMPACT world+ website, http://www.impactworldplus.org/en/team.php

International Panel on Climate Change (IPCC) (2006). *2006 IPCC guidelines for National Greenhouse Gas Inventories*.

ISO. (2005a). ISO 14040 - Environmental Management - life cycle assessment - Principles and framework: International Organization for Standardization.

ISO. (2005b). ISO 14044- Environmental Management- Life cycle assessment- Requirements and guidelines: International Organization for Standardization.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., et al. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment, 8*(6), 324-330.

Millenium Ecosystem Assessment. (2005). *Ecosystems and Human Well-Being: Synthesis.* Washington, DC: Island Press.

Mitchell, J. (2004). *Petroleum Reserves in Question*. London, United Kingdom: Oxford Institute for Energy Studies.

Muller-Wenk, R. (1998). *Depletion of abiotic resources weighted on base of "virtual" impacts of lower grade deposits used in the future*: Universitat St. Gallen.

Nordhaus, W. (2009). *The economics of an integrated world oil market*. Keynote address, International Energy Workshop, Venice, Italy, June 17-19, 2009.googl

OECD. (2008). *Measuring material flows and resource productivity- Volume III. Inventory of country activities*. Paris: OECD.

Owen, N. A., Inderwildi, O. R., & King, D. A. (2010). The status of conventional world oil reserves,ÄîHype or cause for concern? *Energy Policy, 38*(8), 4743-4749.

Pieprzyk, B., Kortluke, R., & Hilje, P. R. (2009). *The impact of fossil fuels: Greenhouse gas emissions, environmental consequences and socio-economic effects*.

Ritthoff, M., Rohn, H., & Liedtke, C. (2002). *Calculating MIPS-Resource productivity of products and services*. Wuppertal: Wuppertal Institut.

Schneider, L., Berger, M., & Finkbeiner, M. (2011). The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources. *The International Journal of Life Cycle Assessment, 16*(9), 929-936.

Society of Petroleum Engineers (SPE). (1997). *Petroleum Reserves Definitions*.

Steen, B. (1999). *A systematic approach to environmental priority strategies in product development (EPS)- Version 2000- Models and data of the default method*: Chalmers University of Technology.

Steinberger, J. K., Krausmann, F., & Eisenmenger, N. (2010). Global patterns of materials use: A socioeconomic and geophysical analysis. *Ecological Economics, 69*(5), 1148-1158.

Stevens, P. (2012). The 'Shale Gas Revolution': Developments and Changes. *Energy, Environment and Resources*.

Stewart, M., & Weidema, B. P. (2005). A Consistent Framework for Assessing the Impacts from Resource Use - A focus on resource functionality (8 pp). *The International Journal of Life Cycle Assessment, 10*(4), 240-247.

Tester, J. W., Drake, E. M., Driscoll, M. J., Golay, M. W., & Peters, W. A. (2005). *Sustainable Energy- Choosing Among Options*. Cambridge, MA: MIT Press.

Toth, F.L., Rogner, H.H. (2006). Oil and nuclrear power: Past, present ,and future. *Energy Economics*, 28 (2006), 1-25.

Udo de Haes, H. (2006). Sustainable Management of Natural Resources in an Life-cycle Perspective (Issue Editor: Helias A. Udo de Haes). *The International Journal of Life Cycle Assessment, 11*(1), 2-2.

UNEP. (2011). *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth*: United Nations Environment Program-International Resource Panel.

Urbina, I. (2011, June 25, 2011). Insiders sound an alarm amid a natural gas rush. *The New York Times*.

US Department of Energy. (2012). *2011 Renewable Energy Data Book*. Prepared for Energy Efficiency and Renewable Energy at US Department of Energy.

USEIA. (2011a). *US Enerngy Information Administration's International Energy Outlook 2011*.

USEIA (2011b). *The World Energy Projection System Plus (WEPS+): An Overview 2011*. Washington, DC: US Department of Energy.

USEIA. (2011c). *The World Energy Projection System Plus (WEPS+): Macroeconomic model*. Washington, DC: US Department of Energy.

USEIA. (2012). *What is shale gas and why is it important?* Retrieved December 20, 2012 from http://www.eia.gov/energy_in_brief/article/about_shale_gas.cfm

US Geological Survey. (2011). *Mineral Commodity Summaries*.

USEIA. (2012). U.S. Energy Information Administration statistics.Retrieved September 2012 from http://www.eia.gov/petroleum/data.cfm - summary

Van Oers, L., de Koning, A., Guinee, J. B., & Huppes, G. (2002). *Abiotic Resource Depletion in LCA*.

World Coal Institute (WEC). (2009) *Coal Resource Overview.* London, United Kingdom: World Coal Institute.

World Energy Council (WEC). (2010). *2010 Survey of Energy Resources*. London, United Kingdom: World Energy Council.

APPENDIX 1 – Midpoint data and characterization factors by country

Table 1- Reserves, annual production rates, R/P values, and FOCSI values for petroleum

COUNTRY	TOTAL RESERVES (MILLION BARRELS)	ANNUAL PRODUCTION (MILLION BARRELS /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
references	*WEC 2010, BP 2011*	*WEC 2010, USEIA 2011*	*N/A*	*N/A*
All countries	1,827,624	30, 700	59.5	1.00

Table 2- Reserves, annual production rates, R/P values, and FOCSI values for coal

COUNTRY	TOTAL RESERVES (MILLION TONNES)	ANNUAL PRODUCTION (MILLION TONNES /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Afghanistan	66	0	N/A	0.00
Albania	794	0	N/A	0.00
Algeria	59	0	N/A	0.00
Argentina	500	0	N/A	0.00
Armenia	163	0	N/A	0.00
Australia	139700	398	351.4	0.37
Bangladesh	293	1	488.3	0.03
Belarus	100	0	N/A	0.00
Bolivia	1	0	N/A	0.00
Bosnia & Herz.	2853	11	254.7	0.61
Botswana	40	1	44.4	1.00
Brazil	12118	7	1836.1	0.00
Bulgaria	2417	29	83.9	1.00
Canada	6582	68	96.7	1.00
Cent. Afr. Rep.	3	0	N/A	1.00
Chile	155	1	310.0	0.48
China	119072	2782	42.8	1.00

Table 2- Reserves, annual production rates, R/P values, and FOCSI values for coal

COUNTRY	TOTAL RESERVES (MILLION TONNES)	ANNUAL PRODUCTION (MILLION TONNES /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Colombia	380	74	5.2	1.00
Congo	88	0<	880.0	0.00
Czech Republic	1100	60	18.3	1.00
Ecuador	24	0	N/A	0.00
Egypt	16	0	N/A	0.00
Georgia	201	0	N/A	0.00
Germany	40699	194	209.4	0.73
Greece	3020	66	46.0	1.00
Greenland	183	0	N/A	0.00
Hungary	3614	9	384.5	0.29
India	60600	516	117.5	0.96
Indonesia	6428	229	28.1	1.00
Iran	1203	3	462.7	0.09
Ireland	14	0	N/A	0.00
Italy	10	0<	100.0	1.00
Japan	350	1	291.7	0.52
Kazakhstan	33600	105	320.3	0.45

Table 2- Reserves, annual production rates, R/P values, and FOCSI values for coal

COUNTRY	TOTAL RESERVES (MILLION TONNES)	ANNUAL PRODUCTION (MILLION TONNES /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Kyrgyzstan	812	2	406.0	0.00
Lao	503	1	838.3	0.00
Malawi	2	0	20.0	1.00
Malaysia	4	1	3.3	1.00
Mexico	1211	12	105.3	0.99
Mongolia	2520	10	257.1	0.61
Montenegro	142	2	83.5	1.00
Mozambique	212	0	N/A	0.00
Myanmar	2	0	6.7	1.00
Nepal	1	0	N/A	0.00
New Caledonia	2	0	N/A	0.00
New Zealand	8644	5	1764.1	0.00
Niger	70	0	350.0	0.38
Nigeria	190	0	N/A	0.00
North Korea	600	33	18.0	1.00
Norway	5	3	1.5	1.00
Pakistan	9077	10	907.7	0.00

Table 2- Reserves, annual production rates, R/P values, and FOCSI values for coal

COUNTRY	TOTAL RESERVES (MILLION TONNES)	ANNUAL PRODUCTION (MILLION TONNES /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Peru	44	0	440.0	0.15
Philippines	316	4	87.8	1.00
Poland	5709	144	39.6	1.00
Portugal	36	0	N/A	0.00
Rep. of Macedonia	332	7	45.5	1.00
Romania	609	35	17.3	1.00
Russia	157010	327	480.9	0.05
Serbia	13770	37	368.2	0.33
Slovakia	262	2	109.2	0.98
Slovenia	223	5	49.6	1.00
South Africa	30156	251	120.1	0.95
South Korea	205	3	73.2	1.00
Spain	530	10	52.0	1.00
Swaziland	144	0	720.0	0.00
Tajikistan	375	1	375.0	0.00
Tanzania	200	0	N/A	1.00
Thailand	1239	18	68.8	1.00

Table 2- Reserves, annual production rates, R/P values, and FOCSI values for coal

COUNTRY	TOTAL RESERVES (MILLION TONNES)	ANNUAL PRODUCTION (MILLION TONNES /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Turkey	2768	79	35.1	1.00
Ukraine	33873	60	567.4	0.00
United Kingdom	383	18	21.2	1.00
United States	237295	1071	221.6	0.70
Uzbekistan	1900	3	612.9	0.00
Venezuela	479	6	74.8	1.00
Viet Nam	150	40	3.8	1.00
Zambia	10	0	50.0	1.00
Zimbabwe	502	3	185.9	0.79
Sources	*WEC report*	*BP 2011*	*N/A*	*N/A*

Table 3- Reserves, annual production rates, R/P values, and FOCSI values for natural gas

COUNTRY	TOTAL RESERVES (BILLION CUBIC METERS)	ANNUAL PRODUCTION (BILLION CUBIC METERS /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Afghanistan	50	0	N/A	0.00
Albania	5	0	N/A	0.00
Algeria	4504	87	52.1	1.00
Angola	161	1	230	0.68
Armenia	164	0	N/A	0.00
Argentina	538	45.2	11.9	1.0
Australia	819	47.5	17.2	1.0
Austria	16	2	8.9	1.00
Azerbaijan	1359	13	108.7	0.98
Bahrain	91	13	7.2	1.00
Bangladesh	344	18	19.2	1.00
Bolivia	710	14	50	1.00
Brazil	245	14	17.3	1.00
Bulgaria	1	0<	3.3	1.00
Cameroon	150	0	N/A	0.00
Canada	1754	167.5	10.2	1.00
Chile	46	1.6	28.8	1.00
China	3160	76.5	41.3	1.00
Columbia	124	9	13.8	1.00

Table 3- Reserves, annual production rates, R/P values, and FOCSI values for natural gas

COUNTRY	TOTAL RESERVES (BILLION CUBIC METERS)	ANNUAL PRODUCTION (BILLION CUBIC METERS /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Congo	92	0.1	460	0.1
Cook Islands	217	7	32.9	1.00
Cote d'Ivoire	42	1	32.3	1.00
Croatia	36	2	22.5	1.00
Cuba	71	0	177.5	0.81
Czech Republic	4	0	20	1.00
Denmark	66	9	7	1.00
Ecuador	9	0	30	1.00
Egypt	2170	48	44.9	1.00
Equatorial Guinea	120	48	2.5	1.00
Ethiopia	25	0	0	1.00
France	7	2	7.8	1.00
Gabon	29	0	290	1.00
Georgia	8	0	0	1.00
Germany	193	15	12.6	1.00
Ghana	24	0	N/A	0.00

Table 3- Reserves, annual production rates, R/P values, and FOCSI values for natural gas

COUNTRY	TOTAL RESERVES (BILLION CUBIC METERS)	ANNUAL PRODUCTION (BILLION CUBIC METERS /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Greece	2	0	N/A	0.00
Hungary	67	3	25.8	1.00
India	1074	32	33.4	1.00
Indonesia	1074	70	45.5	1.00
Iran	29610	116	254.6	0.61
Iraq	3170	10	317	0.5
Ireland	10	0	25	1.00
Italy	119	9	13.2	1.00
Japan	51	3.9	13.1	1.00
Jordan	15	0	50	1.00
Kazakhstan	6500	23	279	0.55
Kuwait	1780	13	140.2	0.9
Kyrgyzstan	6	0	N/A	0.00
Libya	1540	16	96.9	1.00
Madagascar	2	0	N/A	0.00
Malaysia	3186	70	45.4	1.00

Table 3- Reserves, annual production rates, R/P values, and FOCSI values for natural gas

COUNTRY	TOTAL RESERVES (BILLION CUBIC METERS)	ANNUAL PRODUCTION (BILLION CUBIC METERS /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Mauritania	28	0	N/A	0.00
Mexico	785	47	16.8	1.00
Morocco	2	0	20.0	1.00
Mozambique	127	3	38.5	1.00
Myanmar	590	12.4	47.6	1.00
Netherlands	1245	80	15.6	1.00
Nigeria	5292	32	166.9	0.83
Norway	2396	99	24.2	1.00
Oman	950	24	39.4	1.00
Pakistan	840	38	22.4	1.00
Papua New Guinea	442	0.1	4420	0.00
Peru	528	4	132.0	0.92
Philippines	2330	57	40.7	1.00
Poland	75	4	18.3	1.00
Qatar	25172	77	326.9	0.43
Romania	149	11	13.9	1.00
Russia	44900	621	72.3	1.00

Table 3- Reserves, annual production rates, R/P values, and FOCSI values for natural gas

COUNTRY	TOTAL RESERVES (BILLION CUBIC METERS)	ANNUAL PRODUCTION (BILLION CUBIC METERS /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Rwanda	57	0	N/A	0.00
Saudi Arabia	7569	80	94.1	1.00
Senegal	10	0	100.0	1.00
Serbia	48	0	480.0	0.05
Singapore	590	12	47.6	1.00
Slovakia	15	0	75.0	1.00
Solomon Islands	442	1	442.0	1.00
Somalia	6	0	0.0	1.00
South Africa	10	3	3.0	1.00
Spain	3	0	30.0	1.00
Sudan	85	0	N/A	0.00
Syria	300	6	50.8	1.00
Tajikistan	6	0	N/A	0.00
Tanzania	24	1	40.0	1.00
Thailand	93	3	32.1	1.00
Trinidad Tobago	704	39	17.9	1.00
Tunisia	92	3	30.7	1.00

Table 3- Reserves, annual production rates, R/P values, and FOCSI values for natural gas

COUNTRY	TOTAL RESERVES (BILLION CUBIC METERS)	ANNUAL PRODUCTION (BILLION CUBIC METERS /YR)	R/P (YEARS)	FOCSI (MJ deprived from future users/MJ extracted)
Turkey	6	0	20.0	1.00
Turkmenistan	8400	66	127.1	0.93
U.A.E.	6432	50	128.1	0.93
Ukraine	787	20	39.7	1.00
United Kingdom	601	68	8.8	1.00
United States	7022	574	12.2	1.00
Uzbekistan	1745	63	27.5	1.00
Venezuela	4983	24	206.8	0.73
Viet Nam	693	29	24.1	1.00
Yemen	555	0	0.0	1.00

APPENDIX 2 – Endpoint characterization factors by country

Table 1- Endpoint characterization factors for coal

COUNTRY	$CF_{endpoint,\ coal}$ $/MJ dissipated
Afghanistan	0.00
Albania	0.00
Algeria	0.00
Argentina	0.00
Armenia	5.60E-04
Australia	2.07E-04
Bangladesh	1.68E-05
Belarus	0.00
Bolivia	0.00
Bosnia & Herz.	3.42E-04
Botswana	5.60E-04
Brazil	0.00
Bulgaria	5.60E-04
Canada	5.60E-04
Cent. Afr. Rep.	5.60E-04
Chile	2.69E-04
China	5.60E-04

Table 1- Endpoint Characterization factors for coal

COUNTRY	$CF_{endpoint, coal}$ $/MJ dissipated
Colombia	5.60E-04
Congo	0.00
Czech Republic	5.60E-04
Ecuador	0.00
Egypt	0.00
Georgia	0.00
Germany	4.90E-04
Greece	5.60E-04
Greenland	0.00
Hungary	1.62E-04
India	5.38E-04
Indonesia	5.60E-04
Iran	5.04E-05
Ireland	0.00
Italy	5.60E-04
Japan	2.91E-04
Kazakhstan	2.52E-04

Table 1- Endpoint Characterization factors for coal

COUNTRY	$CF_{endpoint, coal}$ $/MJ dissipated
Kyrgyzstan	0.00
Lao	0.00
Malawi	5.60E-04
Malaysia	5.60E-04
Mexico	5.54E-04
Mongolia	3.42E-04
Montenegro	5.60E-04
Mozambique	0.00
Myanmar	5.60E-04
Nepal	0.00
New Caledonia	0.00
New Zealand	0.00
Niger	2.13E-04
Nigeria	0.00
North Korea	5.60E-04
Norway	5.60E-04
Pakistan	0.00

Table 1- Endpoint Characterization factors for coal

COUNTRY	$CF_{endpoint,\ coal}$ \$/MJ dissipated
Peru	8.40E-05
Philippines	5.60E-04
Poland	5.60E-04
Portugal	.00
Rep. of Macedonia	5.60E-04
Romania	5.60E-04
Russia	2.80E-05
Serbia	1.85E-04
Slovakia	5.49E-04
Slovenia	5.60E-04
South Africa	5.32E-04
South Korea	5.60E-04
Spain	5.60E-04
Swaziland	720.0
Tajikistan	0.00
Tanzania	5.60E-04
Thailand	5.60E-04

Table 1- Endpoint Characterization factors for coal

COUNTRY	$CF_{endpoint, coal}$ $/MJ dissipated
Turkey	5.60E-04
Ukraine	0.00
United Kingdom	5.60E-04
United States	3.92E-04
Uzbekistan	0.00
Venezuela	5.60E-04
Viet Nam	5.60E-04
Zambia	5.60E-04
Zimbabwe	4.42E-04
World Average, weighted	**4.64E-04**

Table 2 – Endpoint characterization factor for petroleum

COUNTRY	$CF_{endpoint,\ petroleum}$ $/MJ dissipated
All countries	4.90×10^{-3}

APPENDIX 3 – Intermediate Matrices for calculating endpoint characterization factors – WEPS output

Table 1 - WEPS+ outputs for world energy consumption by energy carrier (x 10^{20} Joules) – Reference scenario

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Liquids	1.90	1.93	1.95	1.98	2.00	2.02	2.04	2.05	2.07	2.08	2.10	2.12	2.15	2.18	2.21	2.24	2.26	2.27	2.28	2.30
Natural Gas	1.27	1.29	1.32	1.34	1.36	1.38	1.41	1.43	1.46	1.48	1.50	1.53	1.55	1.58	1.61	1.63	1.66	1.68	1.71	1.74
Coal	1.60	1.62	1.64	1.66	1.66	1.67	1.69	1.71	1.74	1.77	1.80	1.83	1.87	1.90	1.93	1.96	1.99	2.02	2.05	2.08
Nuclear	0.32	0.33	0.34	0.35	0.36	0.37	0.39	0.40	0.41	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.48	0.49	0.50	0.51
Renewables	0.64	0.66	0.70	0.72	0.75	0.79	0.82	0.84	0.87	0.89	0.91	0.93	0.95	0.97	0.99	1.00	1.02	1.04	1.06	1.08

Table 2- World Energy prices (US Dollars per million BTUs) – Reference Scenario

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Liquids	1.62	1.69	1.75	1.81	1.87	1.92	1.97	2.02	2.07	2.11	2.15	2.19	2.22	2.25	2.28	2.30	2.32	2.34	2.36	2.37
Natural Gas	0.40	0.41	0.41	0.45	0.49	0.51	0.52	0.56	0.58	0.60	0.64	0.64	0.68	0.70	0.76	0.80	0.84	0.89	0.94	0.95
Coal	0.35	0.35	0.35	0.36	0.36	0.36	0.36	0.36	0.37	0.37	0.37	0.38	0.38	0.39	0.40	0.40	0.40	0.41	0.41	0.42
Nuclear	0.23	0.22	0.21	0.21	0.20	0.20	0.19	0.18	0.18	0.17	0.17	0.16	0.16	0.15	0.15	0.15	0.14	0.14	0.13	0.13
Renewables	0.25	0.24	0.23	0.23	0.22	0.21	0.21	0.20	0.20	0.19	0.18	0.18	0.17	0.17	0.16	0.16	0.15	0.15	0.15	0.14

Table 3 - WEPS + outputs for world energy consumption by energy carrier (x 10^20 Joules) - 1 cent per BTU for coal scenario

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Liquids	1.90	1.93	1.95	1.97	2.00	2.02	2.04	2.05	2.07	2.08	2.10	2.12	2.15	2.18	2.21	2.24	2.26	2.27	2.28	2.30
Natural Gas	1.27	1.29	1.32	1.34	1.36	1.38	1.41	1.43	1.46	1.48	1.50	1.53	1.55	1.58	1.61	1.63	1.66	1.68	1.71	1.74
Coal	1.60	1.62	1.64	1.66	1.66	1.67	1.69	1.71	1.74	1.77	1.80	1.83	1.87	1.90	1.93	1.96	1.99	2.02	2.05	2.08
Nuclear	0.32	0.33	0.34	0.35	0.36	0.37	0.39	0.40	0.41	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.48	0.49	0.50	0.51
Renewables	0.64	0.66	0.70	0.72	0.75	0.79	0.82	0.84	0.87	0.89	0.91	0.93	0.95	0.97	0.99	1.00	1.02	1.04	1.06	1.08

Table 4 - Total Additional Costs (TAC) matrix for coal (x 10^6 Dollars)

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Liquids	0.00	0.00	-0.33	-0.17	-0.53	-0.36	-0.56	-0.77	-0.98	-1.00	-1.22	-1.45	-1.68	-1.92	-1.94	-2.18	-2.64	-2.89	-3.13	-3.37
Natural Gas	11.59	18.32	24.83	34.72	42.10	48.88	54.61	64.70	72.04	81.06	90.97	94.98	107.6	116.0	131.6	145.6	158.9	174.2	189.1	197.4
Coal	229.8	231.9	233.8	236.1	235.2	237.4	240.3	243.4	247.0	251.9	256.6	261.4	266.6	271.2	276.2	281.0	286.0	290.7	295.7	300.4
Nuclear	-0.04	0.00	0.00	0.00	0.00	-0.02	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Renewables	-0.07	-0.11	-0.16	-0.06	-0.04	-0.02	-0.02	-0.06	-0.06	-0.09	-0.09	-0.05	-0.05	-0.06	-0.09	-0.11	-0.12	-0.14	-0.17	-0.17

Table 5 - Total Additional Costs (TAC) matrix for petroleum (x 10^6 Dollars)

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Liquids	180.2	179.4	178.3	177.6	178.1	179.8	180.9	181.5	181.8	182.4	184.1	186.4	189.0	192.3	195.3	197.7	200.0	201.5	202.9	204.3
Natural Gas	-2.39	-3.72	-4.72	-6.45	-7.64	-7.26	-6.93	-6.93	-6.66	-6.44	-6.34	-5.54	-6.01	-5.45	-5.35	-5.02	-4.48	-4.22	-3.75	-3.14
Coal	-0.36	-0.57	-0.74	-0.99	-1.05	-1.14	-1.08	-1.11	-1.11	-1.06	-1.13	-1.10	-1.13	-1.09	-1.10	-1.10	-1.08	-1.13	-1.08	-1.11
Nuclear	-0.04	-0.04	-0.02	0.00	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Renewables	-0.09	-0.14	-0.22	-0.22	-0.25	-0.18	-0.16	-0.15	-0.11	-0.11	-0.10	-0.08	-0.05	-0.03	-0.03	-0.03	-0.01	0.00	0.00	0.01

APPENDIX 4 – Data regarding the indirect impacts

Table 1- Total additional consumption (TACON) as a consequence of marginal depletion of petroleum

Sector/ Energy Carrier	TACON (2012-2031)	Unit
Residential Sector		
Petroleum	-2.29	MJ
Natural Gas	0.52	MJ
Coal	0.05	MJ
Renewables	0	MJ
Commercial Sector		
Petroleum	-1.10	MJ
Natural Gas	0.20	MJ
Coal	0	MJ
Renewables	0	MJ
Industrial Sector		
Petroleum	-4.46	MJ
Natural Gas	-3.60	MJ
Coal	-2.63	MJ
Renewables	-1.08	MJ
Transportation Sector		
Petroleum	-7.76	MJ
Natural Gas	-0.19	MJ
Coal	0	MJ
Renewables	0	MJ
Electricity		
Petroleum	-0.21	MJ
Natural Gas	-2.14	MJ
Coal	-3.49	MJ
Nuclear	-0.09	MJ
Renewables	-0.08	MJ

Table 2- Total additional consumption (TACON) as a consequence of marginal depletion of coal

Sector/ Energy Carrier	TACON (2012-2031)	unit
Residential Sector		
Petroleum	0.0013	MJ
Natural Gas	-0.43	MJ
Coal	0.05	MJ
Renewables	0	MJ
Commercial Sector		
Petroleum	0	MJ
Natural Gas	-0.22	MJ
Coal	0.015	MJ
Renewables	0	MJ
Industrial Sector		
Petroleum	-0.091	MJ
Natural Gas	-0.079	MJ
Coal	-0.0052	MJ
Renewables	-0.032	MJ
Transportation Sector		
Petroleum	-0.009	MJ
Natural Gas	0.09	MJ
Coal	0	MJ
Renewables	0	MJ
Electricity		
Petroleum	0.0085	MJ
Natural Gas	4.40	MJ
Coal	-6.25	MJ
Nuclear	-0.042	MJ
Renewables	-0.0026	MJ

APPENDIX 5 – Data regarding SimaPro modelling

Table 28 - Petroleum in the transportation sector

Mode of transport	Percentage	Ecoinvent process(es) selected	Comments
Road-light vehicles	59% 2.0%	Operation, passenger car, petrol, fleet average 2010/ RER U Operation, passenger car, ethanol 5%/CH U	Operation of an average passenger car in the European Union. Operation, passenger car for ethanol was the only available process for biofuels in light vehicles
Road-Trucks	22.2% 0.8%	Operation-Lorry, 3.5-20t, fleet average/RER U Operation-Lorry 28t, rape methyl esther 100%, CH U	Lorries (trucks) range from 3.5 to 20 tons in ecoinvent. The selected process is the average in the European Union for all trucks. Operation of 28t lorry with rape methyl esther is the only available process in Ecoinvent for biofuels for trucks.
Air	8%	Operation, aircraft, freight, RER; Operation, aircraft, intercontinental; Operation, aircraft, freight, Europe	Since no data was found on the share of each process in air transportation, an average of the three air transportation processes available in Ecoinvent was taken. No data available in Ecoinvent for air transportation using biofuels
Water	5%	Operation, barge tanker; operation, barge; operation, transoceanic freight ship; operation, transoceanic tanker	Since no data was found in literature on the percentage share of each of these modes of transport in the total water transportation sector, it was assumed that water travel was equally divided between these four types of water transport. No data available in Ecoinvent for air

			transportation using biofuels
Rail	2%	Operation, freight train, diesel	The only available process in Ecoinvent for trains using petroleum as fuel. No data available in Ecoinvent for rail transportation using biofuels
Road-buses	1%	Operation, regular bus, CH	Operation of a regular bus in Switzerland. The only available process for bus operation in Ecoinvent. No data available in Ecoinvent for bus transportation using biofuels

Table 29 - Natural Gas in the transportation sector

Mode of transport	Percentage	Ecoinvent process(es) selected	Comments
Pipeline	97	Transport, natural gas, pipeline, long distance/ RER	-
Road	3	Operation of a car using natural gas in Switzerland	-

Table 30- World coal electricity production

Country	Share of world coal electricity production	Share of world coal electricity production increased proportionally to add up to 100%
China	48.8	70.2
Austria	0.1	0.1
Belgium	0.1	0.1
Czech Republic	0.5	0.7
Germany	2.2	3.2
United States	15	21.9
Spain	0.3	0.4
France	0.3	0.4
Croatia	0.0	0.0
Italy	0.4	0.6
Slovakia	0.2	0.3
Poland	1.5	2.2

Table 30- World natural gas electricity production

Country	Share of world natural gas electricity production	Share of world natural gas electricity production increased proportionally to add up to 100%
Austria	0.3	0.8
Belgium	0.3	0.8
Germany	2.6	6.9
Spain	1.1	3.0
Great Britain	3	7.97
Italy	2.4	6.38
Japan	3	7.97
Luxembourg	0.3	0.8
Netherlands	1.4	3.8
United States	21.7	0.58

Table 31- Electricity by renewables -HydroPower

Country	Share of world hydropower energy production	Share of world hydropower energy production increased proportionally to add up to 100%
Austria	1.0%	6.02%
Switzerland	1.1%	6.63%
Czech Republic	0.1%	0.6%
Germany	0.6%	3.61%
Spain	1.2%	7.23%
Finland	0.4%	2.41%
France	1.8%	10.84%
Great Britain	0.1%	0.6%
Greece	0.2%	1.20%
Italy	1.4%	8.43%
Japan	2.5%	15.06%
Norway	3.4%	20.48%
Poland	0.1%	0.60%
Portugal	0.5%	3.01%
Sweden	2.0%	12.05%
Slovakia	0.2%	1.20%

Table 32- Electricity by renewables - Solar

Country	Share of world solar energy production	Share of world solar energy production increased proportionally to add up to 100%
Austria	0.3%	0.3%
Australia	1.3%	1.4%
Belgium	2.0%	2.2%
Canada	0.5%	0.5%
Switzerland	0.3%	0.3%
Czech Republic	4.9%	5.3%
Germany	43.5%	47.5%
Spain	9.8%	10.7%
France	2.6%	2.8%
Great Britain	0.2%	0.2%
Greece	0.5%	0.5%
Italy	8.6%	9.4%
Japan	9.1%	9.9%
South Korea	1.4%	1.5%
Portugal	0.3%	0.3%
United States	6.9%	6.9%

APPENDIX 6– Linear interpolation

Using interpolation requires that we identify the nature of the changes in the vicinity of where the perturbation is applied. A fossil resource was selected and the price of the fossil resource was changed by a constant for all years up to 2035. WEPS was used to calculate the total energy costs (as explained in section) for each of these scenarios. The total additional energy costs were calculated for each scenario. Using the acquired data, the nature of the curve of the total additional energy costs versus the change in price of the fossil resource was studied. The plots for this data are presented for petroleum and coal in figures 38 and 39 respectively. In both cases, the relationship is observed to be linear. This allows us to use linear interpolation for calculating the total increase in energy costs due to a marginal cost increase.

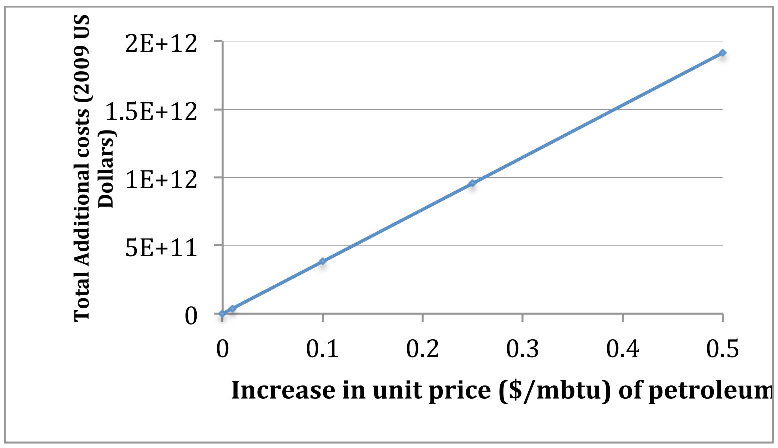

Figure 37-Total Additional Costs (TAC) as a consequence of an increase in the price of petroleum

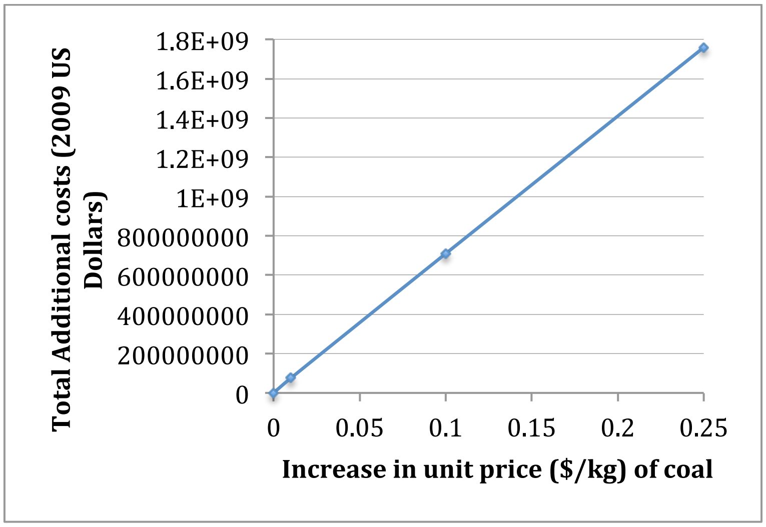

Figure 38-Total Additional Costs (TAC) as a consequence of an increase in the price of coal.

APPENDIX 7 – Comparison of characterization factors from current LCIA methods

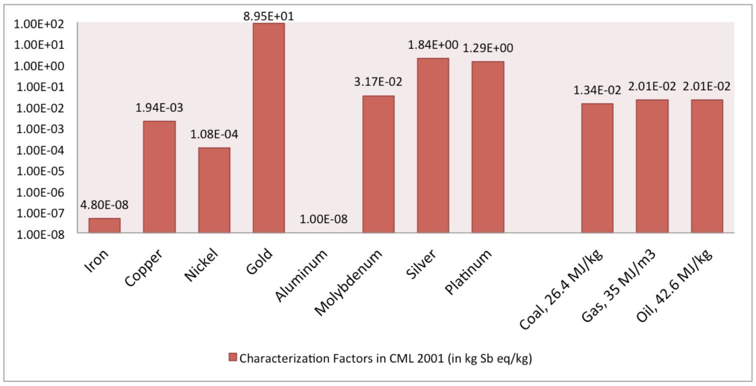

Figure 1 - Characterization factors in CML 2002 (in kg Sb equivalent/kg)

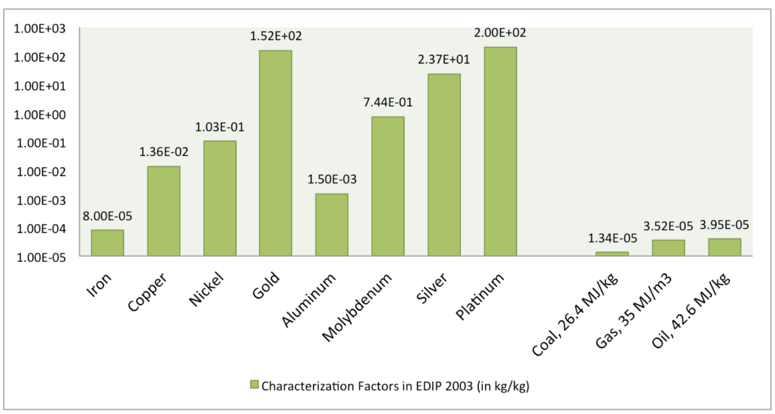

Figure 2 - Characterization factors in EDIP (in kg/kg)

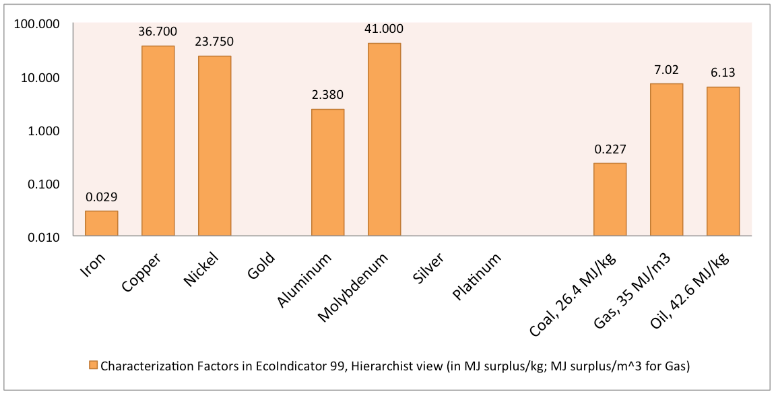

Figure 3 - Characterization factors in Ecoindicator 99, Hierarchist view (in MJ surplus/kg, MJ/m^3 for natural gas)

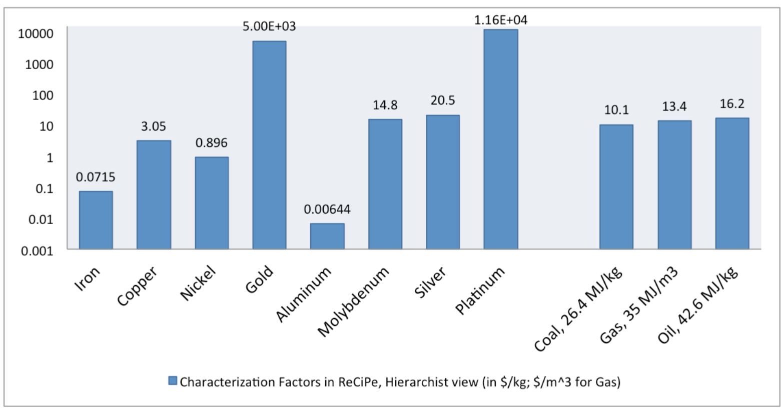

Figure 4 - Characterization factors in ReCiPe (2009) ($/kg, $/m^3 for natural gas)

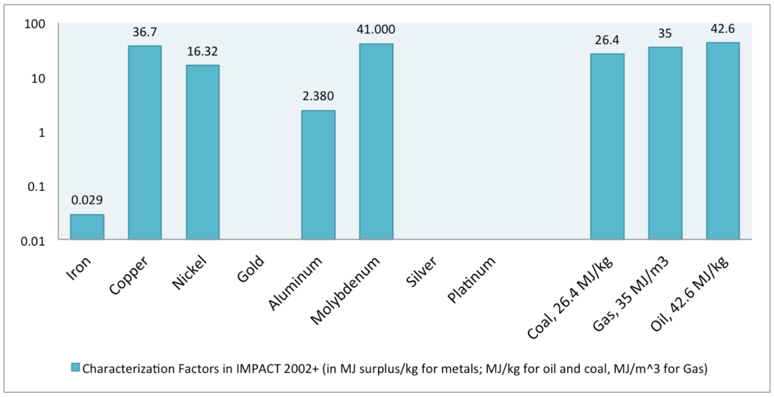

Figure 5- Characterization factors in Impact 2002+ (in MJ surplus/kg for metals, MJ/kg for coal and petroleum, and MJ/m^3 for natural gas)

Quantities of fossil resources used in six processes

Concrete block, 1 kg, at plant		
Material	Amount	Unit
Coal	0.009	kg
Gas	0.001	m3
Oil	0.006	kg
Iron	0.002	kg
Copper	0.00003	kg
Nickel	0.0001	kg
Gold	~ 0	kg
Aluminium	0.00005	kg
Molybdenum	~ 0	kg
Silver	~ 0	kg
Platinum	~ 0	kg

Aluminum Alloy, AlMg3 1 kg, at plant		
Material	Amount	Unit
Coal	1.09	kg
Gas	0.36	kg
Oil	0.29	kg
Iron	0.024	kg
Copper	0.004	kg

Nickel	0.0007	kg
Gold	~ 0	kg
Aluminium	0.22	kg
Molybdenum	0.00005	kg
Silver	~ 0	kg
Platinum	~ 0	kg

Sugar 1 kg, from sugar beet, at sugar refinery		
Material	Amount	Unit
Coal	0.03	kg
Gas	0.07	m3
Oil	0.03	kg
Iron	0.008	kg
Copper	0.00007	kg
Nickel	0.0003	kg
Gold	~ 0	kg
Aluminium	0.0004	kg
Molybdenum	~ 0	kg
Silver	~ 0	kg
Platinum	~ 0	kg

Paper, newsprint, at plant		
Material	Amount	Unit
Coal	0.12	kg

Gas	0.126	m3
Oil	0.107	kg
Iron	0.0056	kg
Copper	0.0001	kg
Nickel	0.00053	kg
Gold	~ 0	kg
Aluminium	0.0021	kg
Molybdenum	0.000002	kg
Silver	~0	kg
Platinum	~0	kg

LCD flat screen, 17 inches, at plant		
Material	Amount	Unit
Coal	87.57	kg
Gas	33.7	m3
Oil	20.3	kg
Iron		
Copper	0.7	kg
Nickel	0.7	kg
Gold	0.0005	kg
Aluminium	1.1	kg

Molybdenum	0.004	kg
Silver	0.001	kg
Platinum	~ 0	kg

Transport, Lorry, 1 tkm		
Material	Amount	Unit
Coal	0.006	kg
Gas	0.004	m3
Oil	0.04	kg
Iron	0.004	kg
Copper	0.00001	kg
Nickel	0.00004	kg
Gold	~0	kg
Aluminium	0.00008	kg
Molybdenum	~0	kg
Silver	~ 0	kg
Platinum	~ 0	kg